

SOLAR-TERRESTRIAL PHYSICS IN THE 1990s:

Key Science Objectives
for the IACG Mission Set

Draft Report of the IACG-ISTP Workshop

San Antonio, Texas
February 5-7, 1991

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NASA

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PREFACE

Beginning in 1992, a series of spacecraft will be launched into the Earth's magnetosphere and nearby solar wind to investigate the source of solar activity, the outflow and propagation of solar plasmas and fields toward the Earth, the response of the Earth's magnetosphere to the various states of the solar wind, and the ultimate deposition of energy into the ionosphere and upper atmosphere. This international solar-terrestrial physics initiative is being pursued jointly by the European Space Agency (ESA), the Japanese Institute of Space and Astronautical Sciences (ISAS), the Soviet Union's Institute for Space Physics (IKI), and the U. S. National Aeronautics and Space Administration. Generally referred to as the International Solar-Terrestrial Physics Program, this set of spacecraft missions, along with their ground-based and theory components and extensive joint mission-planning and data-pooling capabilities, is being coordinated by the Interagency Consultative Group for Space Science (IACG).

In preparation for the upcoming launch dates of the first ISTP spacecraft, the IACG is setting out to update the science objectives of the program and the plans for the effective coordination of the IACG mission set. As an early step in this activity, the U. S. ISTP community, at the request of Dr. Lennard Fisk, is reviewing the ISTP science objectives and implementation plans to provide inputs to the larger IACG study. This draft report is the result of a three-day workshop, which was held in San Antonio, Texas, from February 5 through February 7, 1991. Participants in the workshop were the following:

M. H. Acuna
M. Ashour-Abdalla
D. N. Baker
J. D. Bohlin
J. L. Burch (Chair)
C. A. Cattell
K. P. Dere
T. E. Eastman
L. A. Frank
S. A. Fuselier
M. L. Goldstein
E. W. Hones

M. K. Hudson
S. M. Krimigis
C. T. Russell
P. H. Scherrer
D. G. Sibeck
G. L. Siscoe
M. F. Thomsen
M. R. Torr
J. H. Waite
E. C. Whipple
D. J. Williams
G. L. Withbroe

SAIC Support:
H. Lancaster
G. Maugham

SwRI Editorial Support:
W. S. Lewis

This report is being circulated to the entire U. S. ISTP community for further inputs and will be submitted to NASA and the IACG as our input to the massive mission coordination activities that are now beginning. We hope that the report reflects the scientific breadth and excitement of the program and previews some of the achievements that can reasonably be anticipated from such a major international scientific undertaking.

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I. INTRODUCTION

The International Solar-Terrestrial Physics (ISTP) program is an internationally coordinated multi-spacecraft mission that will study the production of the supersonic magnetized solar wind, its interaction with the Earth's magnetosphere, and the resulting transport of plasma, momentum and energy through the magnetosphere and into the ionosphere and upper atmosphere. The mission will involve 14 spacecraft to be launched between 1992 and 1996, along with complementary ground-based observations and theoretical programs. A list of the spacecraft, their nominal orbits, and responsible agencies is shown in Table 1.

Overall Science Objective

The overall science objective of the program is to improve our quantitative understanding of the solar-terrestrial system by (1) determining structure and dynamics in the solar interior and their role in driving solar activity; (2) identifying processes responsible for heating the solar corona and its acceleration outward as the solar wind; (3) determining the flow of mass, momentum and energy through geospace; (4) gaining a better understanding of the turbulent plasma phenomena that mediate the flow of energy through geospace, particularly in association with the various plasma boundary regions; and (5) implementing a systematic approach to the development of the first global solar-terrestrial model, which will lead to a better understanding of the chain of cause-effect relationships that begins with solar activity and ends with the deposition of energy in the upper atmosphere.

Components of the Solar-Terrestrial System

The solar-terrestrial system includes the Sun, the interplanetary medium, the magnetosphere, the ionosphere, and the upper atmosphere. Each of these regions needs to be studied as an entity, but the interfaces among them and the coupling that takes place across these interfaces determine the behavior of the solar-terrestrial system.

The Sun is an excellent example of this interplay between internal processes and processes that produce external effects in adjacent regions. Since it is the solar wind that interacts most directly with the magnetosphere, one might suppose that a solar-wind monitor is all that is needed to assess the solar input. However, a true understanding of the solar-terrestrial system requires that we probe the interior of the Sun as well as the inner regions of the solar corona in order to understand the origins of solar activity, the heating of the solar corona, and the acceleration of the corona to form the solar wind. A predictive capability for solar-terrestrial disturbances must begin with an understanding of solar variability. One important objective of the ISTP mission is an understanding of this variability.

The interplanetary medium is filled with the solar wind, which carries mass, momentum and energy between the Sun and the planets. Although the solar wind never stops blowing, it is far from quiescent or steady. It is penetrated by high-speed streams and by many turbulent phenomena including interplanetary shocks. Even far upstream of the Earth the solar wind feels the effects of its interaction with the magnetosphere. This foreshock region is characterized by numerous populations of waves and plasmas, which

can be generated both at one of the turbulent interfaces between the solar wind and the magnetosphere, such as the bow shock or magnetopause, and within the magnetosphere itself in association with magnetospheric substorms. Monitoring the solar wind upstream of the magnetosphere and providing the linkage between the solar surface, atmosphere, and interplanetary medium are two important functions of the upstream observations from the ISTP spacecraft.

The disturbed solar wind upstream of Earth, the magnetosphere, the ionosphere, and the upper atmosphere collectively comprise the region known as geospace. The solar wind interacts with the magnetosphere by injecting plasma into it and by transferring momentum through several possible turbulent processes including reconnection and plasma instabilities such as the Kelvin-Helmholtz instability. Although only about 1% of the solar-wind plasma impinging upon the magnetosphere actually enters it, a much larger fraction of the solar-wind momentum is transferred to the magnetosphere by electric-current systems that are set up on the magnetopause and extend down along the magnetic field lines into the ionosphere. In addition to the solar-wind source, the ionosphere represents a vast reservoir of plasma situated within the magnetosphere and capable of providing it with plasma in the observed quantities. The fraction of magnetospheric plasma that originates in the Sun versus that coming from the ionosphere is not known with high precision, but the ISTP program is designed to address this important question.

Several times a day, on average, the magnetosphere undergoes a substorm, which appears to be a fundamental disturbance mode of the magnetosphere. Following southward turnings of the interplanetary magnetic field, the disturbance level of the magnetosphere grows slowly at first and then explosively as the substorm expansion phase begins. It is during substorms that the largest fraction of the incident solar wind energy is dissipated within the magnetosphere, ionosphere, and upper atmosphere. During these impulsive events the large-scale neutral-sheet current system, which helps to maintain the magnetotail, is apparently diverted into the ionosphere, resulting in violent auroral displays, the acceleration of charged particles to high energies, the emission of intense plasma waves and electromagnetic waves such as the auroral kilometric radiation, and the generation of strong ionospheric currents that produce significant Joule heating, neutral winds, and compositional changes in the upper atmosphere. Indeed, the repetitive nature of substorms, their widespread effects, and their fundamental importance in the overall response of the geospace region to solar activity make them a prime target of ISTP and the anticipated sternest test of the multispacecraft coordination that is the hallmark of the program.

Mission Approach

The ultimate goal of ISTP is to achieve significant progress toward a first quantitative global model of the solar-terrestrial environment. A better understanding of the solar-terrestrial system and a first-order predictive capability are expected to result from the combined experimental and theoretical efforts. By far the most ambitious undertaking in space physics to date, ISTP will represent a consolidation of space-based research that began in the earliest days of the space age. That era was also marked by the International Geophysical Year, itself representing a consolidation of research effort using extensive ground-based measurement facilities, sounding rockets and balloons, which had been

Table 1: ISTP Core Missions and Some Complementary Missions

<u>Mission</u>	<u>Agency</u>	<u>Launch</u>	<u>Orbit</u>
Geotail	ISAS/NASA	July 1992	Deep magnetotail ¹ ; later 8 x 30 R _E equatorial
Wind	NASA	Dec. 1992	Near-Earth solar wind ² ; later L1 halo orbit
Polar	NASA	June 1993	800 km x 8 R _E polar
Regatta-A	IKI	1995	2 R _E x 20 R _E polar
Cluster (4 s/c)	ESA/NASA	Dec. 1995	2 R _E x 20 R _E polar
SOHO ³	ESA/NASA	June 1995	L1 halo orbit
CRRES ⁴	NASA	July 1990	Geosynchronous transfer
FAST ⁵	NASA	Sept. 1994	350 x 4200 km, 83°
SAMPEX ⁶	NASA	June 1992	580 km, circular, 82° inclination
Interball	IKI	1991	Tail probe, 500 x 200,000 km; Auroral probe, 500 x 20,000 km ⁷

¹Deep magnetotail orbit maintained by lunar swingbys and on-board propulsion
²Near-Earth solar-wind orbit maintained by lunar swingbys and on-board propulsion
³SOHO - Solar and Heliospheric Observatory
⁴CRRES - Combined Release and Radiation Effects Satellite
⁵Fast Auroral Snapshot
⁶Solar Anomalous and Magnetospheric Particle Explorer
⁷Both have inclinations of 65°

developed over many years of geophysical research throughout the world. Later, in 1976-1980, several spacecraft missions (including ISEE 1 and 2 and Geos 1 and 2) were augmented by ground-based facilities in the International Magnetospheric Study (IMS). The IMS was built around missions that had already been planned and that would have been implemented separately; but the IMS provided a context for increased cooperation on an international basis and in general brought more measurement power to bear on the problems and the investigative intervals that were the focus of study during that period.

During the IMS, plans for ISTP were first formulated for the proposed OPEN (Origins of Plasmas in the Earth's Neighborhood) mission. International interest in the program grew rapidly until a coordinated approach to the problem of the large-scale flow of mass, momentum, and energy through the solar-terrestrial system was formulated. Thus, the

space-based *exploratory* phase of solar-terrestrial research, which began with the IGY, was followed by the the phase of *qualitative understanding* with the IMS and subsequent missions such as Dynamics Explorer. Now we are prepared to enter the era of *quantitative understanding* with ISTP.

ISTP is a natural follow-on to the previous international collaborative research programs IGY and IMS. And yet, it is fundamentally different in that it has been created as a joint program with each additional mission added before the fact to fill certain gaps that had been identified. The international cooperation is built into each mission as well as across the entire program, with an extensive infrastructure of spacecraft operations planning and data pooling capabilities that become part of a coordinated approach possessing synergy far beyond what any predecessor program has been able to achieve. Unlike earlier programs, the theoretical, modeling, and ground-based elements of ISTP have been included from the outset and have developed significantly during the planning and instrument-development phases of the program. For example, MHD models that have been developed can be used for mission planning purposes; for early assessment of key parameter data, in terms of where in geospace the data were acquired; as well as for detailed data interpretation.

Anticipated Accomplishments

Numerous significant scientific accomplishments will surely be credited to the ISTP program. A number of these can be predicted with some certainty; others, hoped for, and still others, anticipated but not predicted because they will result from the new measurement capabilities inherent in the program. Ranging from new discoveries to quantitative understanding of previously known phenomena, the expected achievements will come from new measurements on individual spacecraft, from multipoint correlative measurements, and from large data sets combined with an extensive program of theory, simulation, and computer modeling. The list is long and truly astounding in its scientific breadth and significance. Taken as a whole, it represents a major advance in knowledge and understanding of the solar-terrestrial system. Even in its breadth, the list is by no means exhaustive. Many accomplishments of the ISTP mission cannot be anticipated since the new instrumentation and fundamentally different approach of the ISTP mission will produce many surprises. The anticipated achievements are listed here by region, beginning with the interior of the Sun and progressing outward and then downward to the upper atmosphere of the Earth.

The Solar Interior

- The average radial structure of the solar interior will be determined.
- The convective motions in the solar interior that transport energy to the surface and that generate the solar cycle will be characterized.
- Solar atmospheric convection will be characterized on scales that govern the growth of active regions.

The Solar Corona

- The first maps of the three-dimensional temperature flow field in the extended corona will be obtained.
- The first high-resolution determinations of the mass flux in coronal holes will be made.
- The first observations of coronal mass ejections will be made throughout the 1–30 solar radii range of radial distances.
- Systematic studies of coronal abundance variations in the solar atmosphere will be made.

The Interplanetary Medium

- The solar wind input into the magnetosphere will be monitored nearly continuously.
- The three-dimensional structure of the solar wind will be determined and mapped to the solar corona or surface.
- The composition and charge states of the solar wind will be measured, and inferred coronal temperatures will be correlated with remote observations of the corona.

Throughout Geospace

- Determination will be made of electric current densities and fluid vorticities.
- Plasma wave modes will be identified; directions of propagation will be determined; and frequency spectra of electromagnetic plasma waves in the magnetosphere, magnetosheath, and solar wind will be obtained.
- The shape and structure of discontinuities in the solar wind and magnetosphere will be determined.
- The modes present in the dissipation range of solar wind MHD turbulence will be identified, and the spatial structure of the magnetic helicity in the inertial range of the turbulence will be determined.
- Four-point magnetic field measurements will be used to quantify the degree of Alfvénic and/or quasi-two-dimensional symmetry of interplanetary MHD fluctuations.
- The relative importance of the solar wind and magnetospheric plasma sources be determined.

The Bow Shock, Foreshock, and Magnetosheath

- The three-dimensional structure and temporal variability of the bow shock and their dependence on solar wind parameters will be determined.
- An understanding of how upstream discontinuities and waves are transmitted through the bow shock will be achieved.
- Determination of how transmitted discontinuities and waves, as well as magnetosheath structure produced at the shock itself, evolve through the magnetosheath and how they affect the coupling between the solar wind and the magnetosphere will be determined.

- Firm identification will be made of the macroscopic and microscopic processes responsible for collisionless shock dissipation, as functions of upstream parameters.

The Magnetosphere

- The transfer rate of mass, momentum, and energy across the magnetopause will be measured.
- The three-dimensional dynamical structure of the polar cusp regions and the flow and composition of plasmas within them will be determined.
- The nature of the variation of the magnetic reconnection process in the mid-latitude (dayside) magnetopause with variations in solar wind magnetic field will be determined.
- The electric fields associated with the reconnection process will be measured.
- Progress will be made in characterizing the thin plasma layers and ion beams found in the auroral acceleration region.
- Measurements of electric and magnetic fields together with plasma flow and composition will be used to construct a quantitative model of magnetotail dynamics.
- The geometry of the cross-tail current and the formation and dynamics of the neutral line and plasmoids will be determined.

The Ionosphere and Upper Atmosphere

- Quantitative global information on the corpuscular energy source will be used to model for the first time the time evolution of the ionospheric and atmospheric response to magnetospheric forcing processes.

II. SCIENCE BACKGROUND

A. CURRENT RESEARCH ARENAS

The physics of the solar-terrestrial environment is determined by the interaction of magnetized conducting gases that exist over vast ranges of densities and temperatures and that interact extensively with one another to produce dynamic research arenas, which are characterized much more by their variability than by any equilibrium state that can be imagined. The research arenas are vast in size and complexity but ordered in terms of the unity with which much of the phenomena can be described. Magnetohydrodynamics and plasma kinetic theory can describe phenomena in the hot, dense solar atmosphere as well as in many other cooler, tenuous plasma domains in the magnetosphere. Wave-particle interactions, particle acceleration, magnetic reconnection, collisionless shocks, turbulence, current generation, Joule dissipation, and many other space-plasma phenomena are common problems throughout the solar-terrestrial system and need to be studied together. It is only now possible to do this with ISTP. The following overviews of the different parts of the system are meant to provide background for the more detailed science discussions contained in the next section.

The Solar Interior

The three main parts of the Sun—the radiative interior, the convective envelope, and the atmosphere—together provide and regulate the major input of energy to the solar-terrestrial system. The Sun also is the source of the ambient magnetic fields and plasmas which interact with the Earth's field. The structure of the solar interior is important to the astrophysical understanding of the Sun, and is also crucial to understanding solar-terrestrial physics. The combination of the convection that occurs in the outer 30% of the Sun and the Sun's rotation is thought to produce the solar dynamo and hence the solar cycle of magnetic activity. Magnetic fields generated in this region are also manifested in the intricate magnetic structure of the solar atmosphere including coronal holes, flares and coronal mass ejections.

The science of helioseismology measures and infers the solar interior structure and motions using observations of surface oscillations. Figure 1 is a cutaway view of the Sun showing a normal mode of surface oscillation and its extension into the solar interior. The light regions are zones of expansion; the dark regions, contraction. Typical oscillation periods range from minutes to hours or more.

With the helioseismology experiments on SOHO it will be possible to determine radial stratification and aspheric variations of pressure, density, composition, sound speed and internal rotation. These measurements may well reveal the source of solar-cycle variations. It will also be possible to probe solar interior convection on all scales from the global structure of the convection zone, through supergranulation and network evolution, to turbulent convection leading to granulation and meso-granulation. The internal structure and detailed magnetic flux history of active regions will be characterized, and a predictive capability for solar activity may well result from these investigations. Finally the response

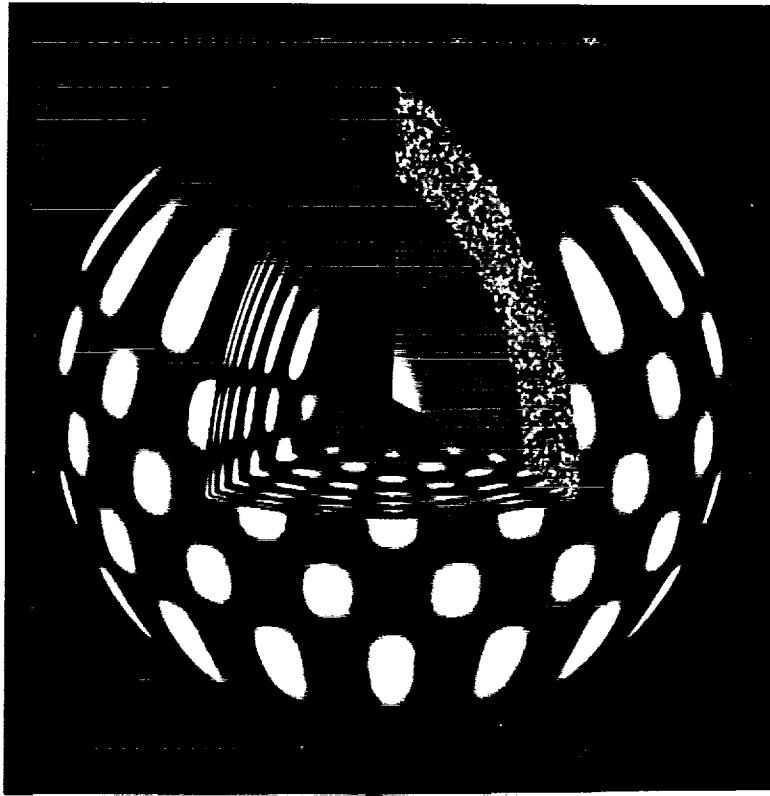


Fig. 1. Schematic drawing of a particular resonant oscillation mode in the Sun. The mode surface pattern and radial structure are shown. This particular mode penetrates nearly to the energy-generating core.

of the solar atmosphere to the convective motions and the magnetic variations will be determined.

The Solar Corona

The outer solar atmosphere is the source of the solar wind, which controls conditions in interplanetary space and the terrestrial magnetosphere. The outer solar atmosphere also produces the short-wavelength radiations (UV to x-ray spectral regions), which are the primary sources of energy to the upper atmosphere of the Earth. An image of the corona is shown in Figure 2.

Knowledge of the physical conditions in the outer solar atmosphere is vital to the development of an understanding of the generation of the solar wind. Although there is substantial empirical information on the density structure of the corona within 5 solar radii of the Sun, there are only isolated measurements of other critical plasma parameters, except close to the surface where observations of spectral line intensities and profiles have provided detailed information. The lack of a detailed empirical description of the physical conditions in the extended corona has inhibited development of an understanding of the heating and acceleration of the coronal plasma to form the solar wind. We still do not know the answers to fundamental questions such as: what are the dominant plasma heating mechanisms? Is coronal heating due to MHD waves, dissipation of magnetic energy, or a

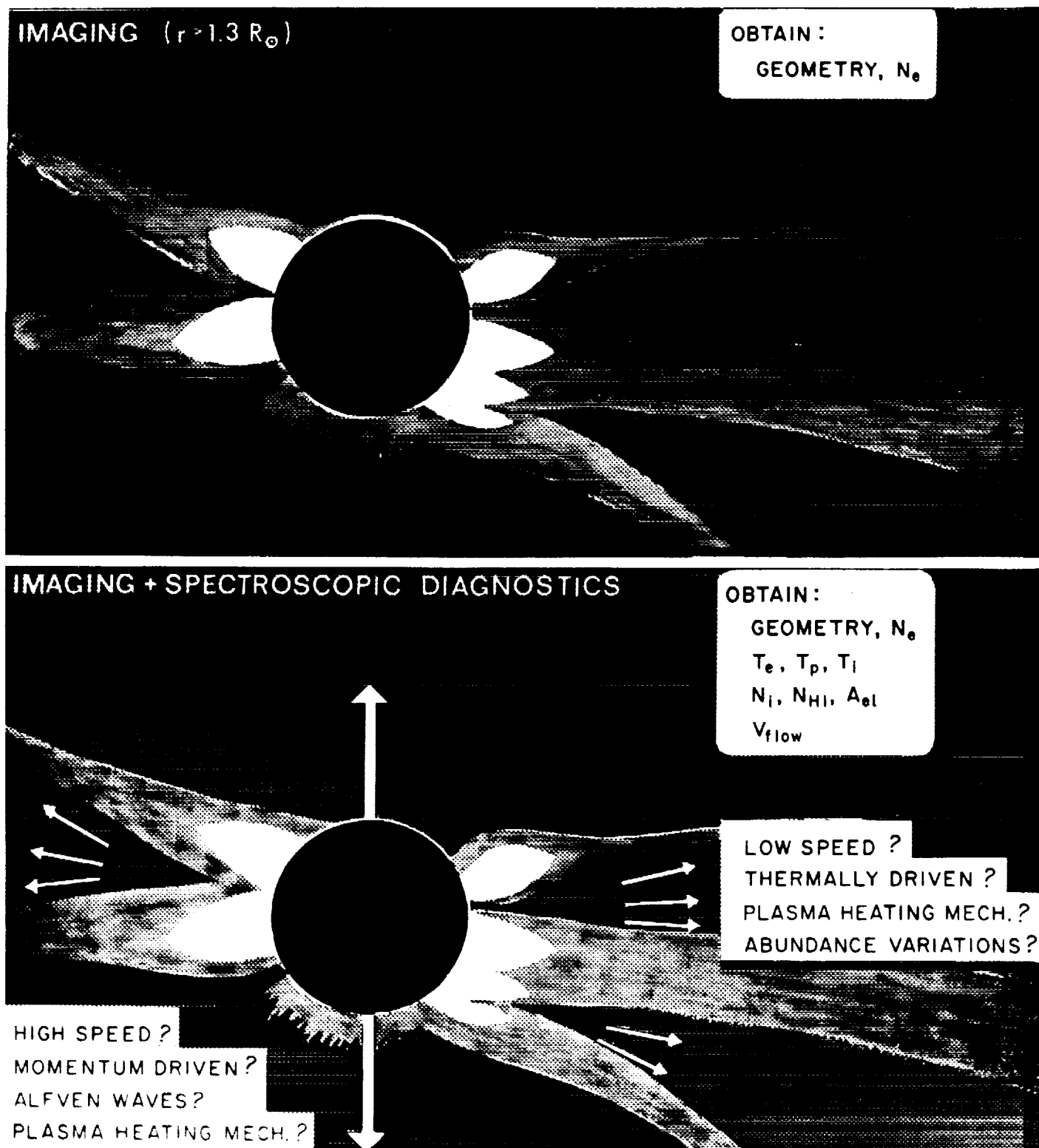


Fig. 2. Images of the solar corona. Measurements made during ISTP will provide the detailed empirical information needed to understand the mechanisms involved in the heating and acceleration of the coronal plasma to form the solar wind.

combination of mechanisms that depend upon the type of region (e.g., magnetically open or magnetically closed)? What are the energy transport and dissipation mechanisms? What are the dominant plasma acceleration mechanisms, thermal pressure gradients (Parker-type wind) or wave-particle interactions? What are the sources of the low-speed wind and the high-speed wind? What is the role of the fine structures in these sources? What fraction, if any, of the wind from these sources is driven by magnetic forces? For example, magnetic forces most likely accelerate coronal mass ejections. Are magnetic forces an important factor in driving the wind from small-scale substructures in regions such as coronal holes? Polar plumes in polar coronal holes are a likely source of wind that could be thermally or magnetically driven, while Alfvén waves are thought to be a possible source of energy for boosting the speed of the thermally driven wind from coronal holes to the high speeds observed near the Earth. Can we confirm this hypothesis by making detailed measurements of the conditions in the coronal source region of the solar wind? How are the heavy ions accelerated? What causes the variations in the chemical composition of the solar wind measured *in situ* far from the Sun? Answers to these questions require improved observations. The optical instruments on SOHO, in combination with *in situ* instruments on SOHO and other ISTP spacecraft can provide the required measurements.

The Foreshock and Bow Shock

Collisionless shock waves have been of high scientific interest for many years, and the *in situ* measurements of shocks in space plasmas obtained by spaceborne instruments have afforded us the unique opportunity to study the structure and dissipation of such shocks at a level of spatial and temporal detail not attainable in the laboratory. Because spacecraft cross the Earth's bow shock relatively slowly and thus can obtain well-resolved measurements within the shock layer itself, the bow shock has been the prime laboratory for the study of collisionless shocks in space. Moreover, the bow shock (and the associated foreshock region) is the first point of contact between the solar wind and the Earth's magnetosphere (see Figure 3). Processes occurring at and near the bow shock alter the nature of the solar-wind flow and determine its properties when it meets the magnetospheric boundary. Because the coupling of solar wind mass, momentum, and energy into the magnetosphere depends strongly on the properties of the magnetosheath plasma, the bow shock plays a strong role in determining the nature and extent of the coupling.

The foreshock, the region just upstream of the bow shock and magnetically connected to it, contains electrons and ions streaming back along field lines from solar wind energies up to 100's of keV. Possible sources for these particles include specular reflection, shock-drift, Fermi acceleration, and leakage from the magnetosheath and magnetosphere. Waves are created in the plasma at frequencies from the electron plasma frequency to well below the ion gyrofrequency. To understand the full gamut of plasma phenomena occurring in the foreshock, the ISTP investigations will need to characterize the source strength and composition of these particle beams and determine how they depend on upstream and downstream conditions and geometry. The ISTP measurements will determine the factors that control the energy of the counterstreaming particles and allow us to infer the underlying acceleration mechanisms; they will determine the spatial structure of the foreshock region, where particles of each type are observed and specify what spatial variations in properties

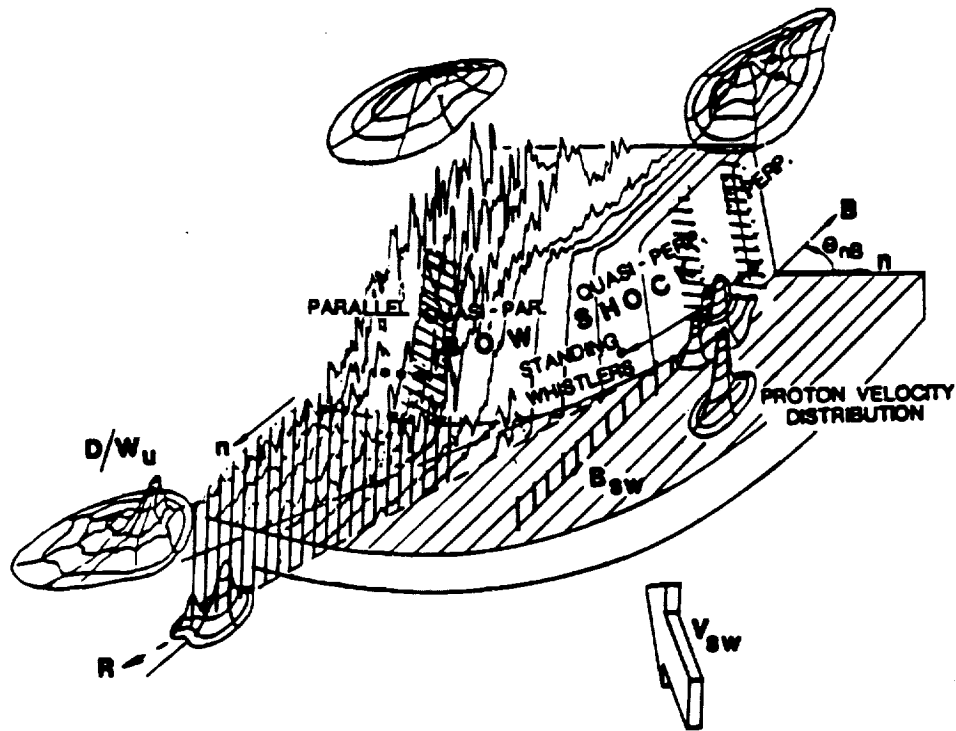


Fig. 3. The overall foreshock environment and its plasma sources and processes. The reflected beams are most evident at the quasi-perpendicular part of the shock, where the IMF is nearly tangent to the shock surface. The more diffuse population appears most often in the quasi-parallel region, as does the higher energy (≥ 50 keV) component that may be associated with direct magnetosphere leakage, perhaps through magnetic merging, or direct Fermi acceleration of the reflected solar wind population.

occur due to variations in source strength or scattering. Finally the ISTP fields and plasmas measurements will characterize the properties of the waves arising in association with the counterstreaming particles more thoroughly than on previous missions.

The Magnetosphere

The magnetosphere is the relatively self-contained region in space whose global topology is organized by the magnetic field associated with the Earth. This field extends far into space and serves to deflect the on-rushing solar wind. The stand-off distance at the subsolar point is highly variable (depending on solar-wind pressure), but is typically about $10 R_E$. The flowing solar wind applies tangential stresses to the outer reaches of the Earth's intrinsic field and sets up a system of currents in the boundary regions. The $\mathbf{j} \times \mathbf{B}$ forces due to these currents act to distort the magnetic field, and field lines are dragged downstream to form a very elongated magnetotail.

The Earth's magnetosphere extends to altitudes of $\sim 10 R_E$ on the dayside, and to more than $1000 R_E$ on the nightside. The solar wind flows continually over, around, and into the terrestrial magnetosphere, and in so doing it continually imparts mass, momentum, and energy to the system. This transfer, however, occurs with great variability. When the

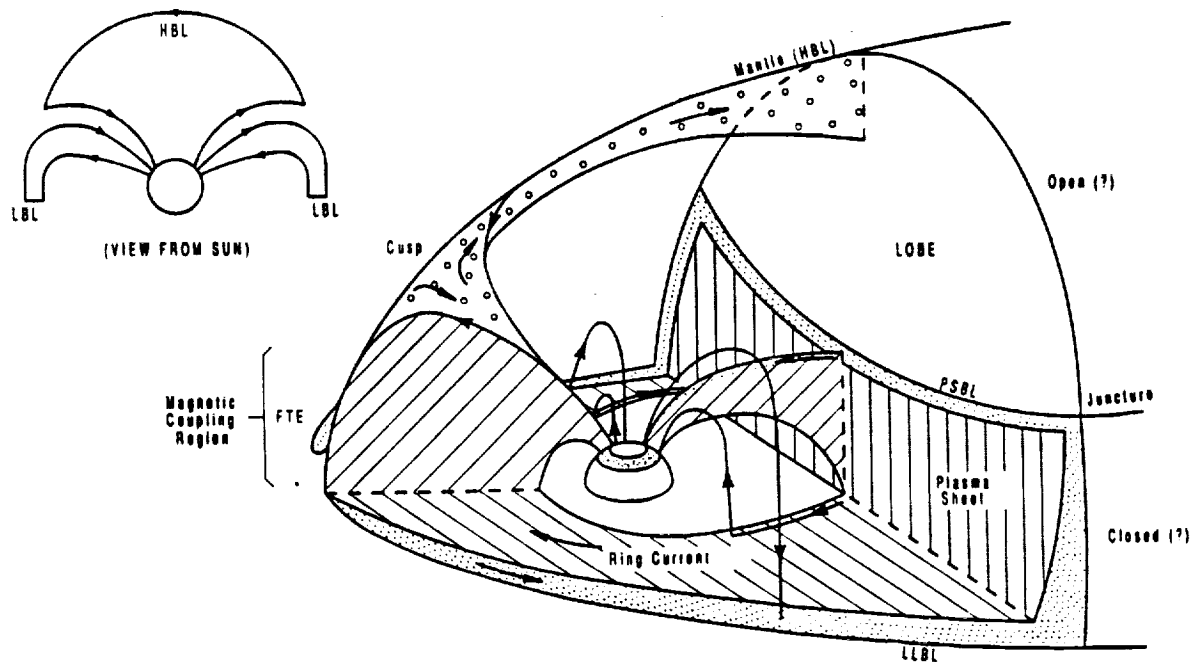


Fig. 4. Key components of the magnetosphere. This schematic also indicates flows that move plasma through the system, motions that change the magnetosphere's shape during the first or growth phase (as an example) of magnetospheric substorms, and paths of electrical currents that feed energy between the ionosphere and different parts of the magnetosphere.

added amount of energy is high, the magnetosphere moves far out of its equilibrium "ground state." The added energy must then be dissipated either continuously or sporadically. It has been found that the dissipation of added solar-wind energy occurs in a very sporadic way, and the sudden occurrence of this magnetospheric dissipation is a major feature of the collection of physical processes that is called a magnetospheric substorm.

Geomagnetic storms are major disturbances in the magnetosphere. As the name suggests, such storms manifest themselves by global changes (for periods of hours to days) in the magnetic (and electric) fields surrounding the Earth. Storms also produce profound changes in the energy distributions and spatial locations of the plasmas filling the magnetosphere. Moderate magnetic storms may occur relatively frequently (every month or so), but great storms due to major solar disturbances usually occur at intervals of many years.

Figure 4 identifies key components of the magnetosphere. It also indicates flows that move plasma through the system, motions that change the magnetosphere's shape during the first or growth phase (as an example) of magnetospheric substorms, and paths of electrical currents that feed energy between the ionosphere and different parts of the

magnetosphere. The cusp, the low-latitude boundary layer, and the bow shock are characterized by complex plasma kinetic processes and turbulence; they, among others, are marked for comprehensive ISTP studies based on the advanced diagnostic capabilities of ISTP instrumentation and on mesoscale synoptic data from the Cluster array. The general circulation, the configurational changes, and the feeder currents are targets for concerted ISTP campaigns based on advanced plasma composition diagnostics to identify sources and on simultaneous multipoint measurements from the ISTP constellation of spacecraft together with ground observations. Geospace itself—interacting parts, general circulation, and coupling currents taken severally or together—will be the focus of extensive efforts by ISTP's contingent of global modelers.

The Ionosphere and Upper Atmosphere

The partially-ionized upper atmosphere of Earth comprises the coexisting ionosphere and thermosphere, where the major dissipation of solar ultraviolet radiation takes place. This region is of crucial importance to the solar-terrestrial environment as a source of magnetospheric plasma, a conductive shell that converts the coupling currents of the solar-wind interaction into a global convection electric field, a resistive element that converts field-aligned currents into Joule heat, and an absorber of the energy carried by auroral particles.

The ionosphere is created by the absorption of solar extreme ultraviolet radiation at altitudes between 100 and 500 km. Predominantly O^+ , O_2^+ , N^+ , and N_2^+ ions are formed. Subsequent ion chemistry creates an E-layer of N_2^+ , O_2^+ , and NO^+ , an F-layer dominated by O^+ , and an upper ionosphere where H^+ , formed from charge exchange of atomic hydrogen with O^+ , serves as the source of the ion outflow known as the polar wind. H^+ dominates the outflow in the more quiescent region of the upper ionosphere owing to its smaller mass and diffusive ambipolar separation. However, in the polar cusp and the nightside auroral oval not only can ion production by solar ultraviolet be significantly modified by ion and electron precipitation, but significant current dissipation from the magnetosphere can also lead to ion outflows more than 50 times those of the quiescent polar wind. O^+ can be the dominant outflowing ion, and large concentrations of O^+ in the magnetosphere are an indication of the significant role the ionosphere can play in supplying plasma to the magnetosphere. In addition, the closure of magnetospheric currents and the role that variable ionospheric conductance plays in the global current structure are an indication of the close coupling of the overall magnetosphere-ionosphere system. The feedback also extends to the atmosphere as well, where ion-neutral collisions drive thermospheric circulation patterns that are clearly dominated by magnetospheric forcing functions at high latitudes.

With ISTP the global input of energy to the ionosphere and thermosphere will be determined by imagers of visible and ultraviolet light and x-rays on the Polar spacecraft, by measurements of solar EUV by SOHO and by ground-based radars, sounders, and magnetometer arrays. When combined with appropriate global circulation models, the ISTP data will lead to a quantified understanding of the propagation and deposition of energy and momentum in the near-Earth zone of the solar-terrestrial system.

B. RESEARCH PLAN

In the arena of solar-terrestrial physics, global aspects are characterized by an amalgam of interdependent parts. Thus, in basic outline, a comprehensive research program for solar-terrestrial physics must progress through a sequence of levels:

1. Learn the parts,
2. Determine how they work,
3. See how they are connected,
4. Assemble them into a working model,
5. Run the model and check its predictions.

In actuality, research proceeds on more than one level, moving fastest on lower levels. Indeed, solar-terrestrial research has progressed far in identifying the structural units of its domain. Accordingly, ISTP will primarily, but not exclusively, address levels 2, 3, and 4. Advanced instrumentation and the Cluster array will provide data to advance significantly our understanding of the physical processes that operate within geospace components. The constellation of ISTP spacecraft, assigned to cover key solar and geospace regions, complemented by networks of ground-based monitors, will enable coordinated studies to address the coupling of the components one to another. The ISTP theory and modeling program will assimilate the findings into global models, which will evolve as knowledge and understanding increase, to simulate with ever greater comprehensiveness and accuracy observed solar-terrestrial phenomena.

In summary, ISTP is aimed broadly at the middle stages of a five-tiered research hierarchy. It emphasizes advanced measurement capabilities to address issues of physical processes and plasma sources, and it adds multipoint measurements—mesoscale, macroscale, and global—and advanced modeling capabilities to address issues of system throughputs, system budgets, and system couplings.

III. NEW CAPABILITIES

Many improvements in resolution and parameter ranges are being incorporated into the scientific instruments of the ISTP spacecraft. Some represent the usual advances expected of state-of-the-art instrumentation; others, such as the SOHO helioseismology instruments, represent a step-function advance or a completely new capability. Additional capabilities, such as closely spaced multiple spacecraft, represent fundamentally new approaches to space-plasma experimentation and others, such as mission-oriented theory, establish completely new ways of conducting a spacecraft mission. Several of the new techniques that characterize the ISTP program are discussed in the following paragraphs.

Multipoint Measurements

Multipoint measurements of the geospace environment have been performed by several preceding spacecraft missions such as Dynamics Explorer and the ISEE spacecraft. However, these missions were built around separated experimental and data handling responsibilities with no built-in modeling and theory program. Although many specific scientific investigations have taken advantage of such multipoint measurements in the past, they have been limited in scope and difficult to implement because of the need for case-by-case custom handling of incompatible data formats and data analysis tools and a lack of baseline models. The ISTP program provides a major advance in such multipoint investigations by setting up, in advance, the framework for a new synergism between theory, modeling and observations. As discussed below, theory and modeling are fully integrated to enable a close interaction between theory and observations. Predictions and needed tests of these models provide the basis for optimal selections of appropriate multipoint observations in a coordinated way. Mode changes in the instruments, adjustments of inter-spacecraft spacing (with Cluster) campaign coordination among spacecraft and ground-based facilities are some of the new tools that ISTP provides to enable quantitative testing of models and theories. For example, model predictions and testing will sometimes motivate, in advance, special spacecraft coordination through instrument changes to burst mode, active changes in charge state and composition coverage, and specification of a campaign interval. Such coordinated multipoint measurements will enable ISTP to carry out quantitative scientific studies far more efficiently and effectively than was previously possible. This effectiveness arises in part from ready and universal access to key parameters and the operation of coordinated data-handling facilities that provide for easy and effective data access.

The ability to make multipoint measurements that are both local (separations of at most a few thousand kilometers) and non-local (separations of a several R_E) within the geospace environment is a unique capability of ISTP, which will enable us to make fundamental advances in our understanding of the mechanisms of energy and momentum transport. The four Cluster spacecraft in their tetrahedral configuration are designed to facilitate determination of the various vector quantities (fluid flow velocities, currents, electric and magnetic fields) that characterize an electromagnetic plasma.

From the four-point measurements, vector curls ($\nabla \times$) of \mathbf{B} and \mathbf{v} will permit determination of the currents and vorticity in the fluids. To determine these quantities, the

data from Cluster must routinely be differenced and a cross-spectral analysis performed to derive wave-numbers. Various techniques are being developed to take full advantage of these unique Cluster capabilities. For example, Stokes' theorem can be invoked to use the tetrahedral configuration of Cluster to determine the current density — a procedure that has been called the *curlometer*. This procedure can be employed for low-frequency waves (frequencies well below the plasma frequency). The accuracy of the technique depends on just how uniform the conditions are within the tetrahedron and works best when the magnetic field can be well approximated by

$$\mathbf{B}(\mathbf{R}+\Delta\mathbf{R}) = \mathbf{B}(\mathbf{R}) + \Delta\mathbf{R} \cdot \nabla\mathbf{B},$$

and $\nabla\mathbf{B}$ is locally constant. When the gradients in the fields are as small as 100 km (as happens at the magnetopause, shocks, FTE's and various boundary layers), the *curlometer* technique will have to be used with caution. Accurate determination of magnetic-field differences to within 0.1 nT between spacecraft separated by as little as 100 km are required, but are expected to be achieved. Other estimates indicate that for inter-spacecraft separations of order 10^3 km current densities of 10^{-9} A m⁻² can be detected.

The *wave telescope* technique is being developed for use when the fields are dominated by waves or turbulence. The basis for this technique is the assumption that the spacecraft are recording fields from an ensemble of plane waves with unique wave vectors, \mathbf{k} —an assumption that should be satisfied for wave sources and wavelengths smaller than the size of the system. The wave telescope technique is less well suited for use in regions where multiple reflections are present. The Cluster assemblage will also be ideally suited for analyzing the shape and flow speed of discontinuities, in particular, to test the usual assumption of planarity.

New Instrumental Capabilities

Spectroscopy and Imaging of the Extended Solar Corona. SOHO will be the first satellite (except for the short-duration SPARTAN-201 mission, scheduled for a 1993 Shuttle flight) with both spectroscopic and imaging capabilities for observations of the extended solar corona.

Spectroscopy. Past satellite observations of the extended solar corona ($1 < r < 10$ solar radii) have been limited to broad-band white light imaging measurements. These provide information on the spatial structure of, and electron densities in, the region where the solar wind is believed to be accelerated to supersonic speed. SOHO will greatly expand the number of parameters measured. It will provide measurements of, or empirical constraints on: coronal electron and hydrogen densities and temperatures; electron-proton flow velocities; ion densities; ion temperatures; ion flow velocities; chemical composition; and constraints on the velocity amplitudes of wave and/or turbulent motions. SOHO will be a significant advance over previous generations of solar satellites by providing the first long-duration, detailed spectroscopic observations of the coronal source region of the solar wind.

Imaging. SOHO will also greatly expand the distances over which imaging data are acquired, out to 30 solar radii from the Sun. This will permit observation of coronal mass ejections to much larger distances from the Sun, out into the interplanetary medium, than was possible with early spacecraft such as Skylab, SOLWIND, and SMM.

Helioseismology. SOHO will also be the first satellite to contain an imaging instrument for measuring solar oscillations. It will provide extensive high-resolution, spatially resolved measurements which can be used for research in helioseismology. In combination with instruments measuring the spatially integrated radiation, SOHO will provide a powerful tool for probing the solar interior using the techniques of helioseismology.

Electric Field Instrumentation. In recent years there have been significant new instrumentation capabilities developed, as well as improvements in established techniques, for the measurement of electric fields.

Electron Drift Technique. On Cluster a unique "test particle" approach will be implemented for the measurement of electric fields through sensing the electron drift velocity. This technique relies upon the fact that for a given electric field, there are two unique directions for which a beam of electrons emitted from the spacecraft will return after a single gyro orbit. The electron drift technique uses a pair of electron guns and detectors to determine both the required firing directions and the time-of-flight for the electrons on these trajectories. The electric field is then determined by triangulation with the firing directions, or by the relative times of flight for the two different directions, depending on the regime. Variation of the beam energy is used to differentiate between electric field and magnetic gradient sources of drift. This approach is expected to have unprecedented sensitivity and to alleviate the problem of spacecraft plasma sheaths, which can sometimes affect the operation of floating-probe electric-field detectors.

The electron drift technique was successfully demonstrated on the GEOS satellites, with a temporal resolution of the satellite spin period. The Cluster implementation will use active beam servoing to provide field measurements at frequencies below approximately 100 Hz. An additional benefit of the electron drift technique is that it provides a highly accurate calibration for the on-board magnetometer.

Double Probe Technique. Data obtained from both the S3-3 and ISEE electric field instruments, showing that nonlinear structures and large-amplitude, small-scale electric field structures occurred in many regions of the magnetosphere, proved that very high time-resolution electric-field observations must be obtained in two or three dimensions in order to understand the physical processes occurring in geospace, particularly in the narrow transition regions where much of the interesting physics occurs. Regions of interest include the auroral zone, the bow shock, the plasma sheet boundary layer, and the neutral sheet. For the latter three regions, measurements could only be made along the spinning boom with a time resolution of ~ 0.02 s, so no information on the actual amplitudes or spatial structure could be obtained. It is quite likely that these structures are as important to an understanding of particle acceleration and dissipation in these regions as they are in the auroral zone. The use of time-domain data to study inherently nonlinear processes and

frequency-domain data to study linear waves is necessary to understand the phenomena of interest because nonlinear structures, such as double layers, look like broad, featureless spectra in the frequency domain, while data containing a superposition of linear waves may look like noise in the time domain but show clear features, such as cutoffs, in a spectrum. The ISTP electric-field instruments will provide the required high-time-resolution data, large burst memories, and flexible operation. Another new capability is that the instrument can be configured to obtain low-energy electron density and temperature data by operating one or more of the probes as a Langmuir probe. In addition, an important improved capability of these instruments is the ability to obtain wavelength information in a variety of ways including examination of wave amplitudes from antennas of differing lengths, use of wave-particle correlators, time delays between different antennas, comparison of simultaneous density and electric-field fluctuations, and comparison of simultaneously sampled electric-field and magnetic-field fluctuations.

UV Imaging. In the area of imaging in the vacuum ultraviolet, very substantial technological advances have been made which greatly enhance what ISTP will be able to achieve compared with previous efforts. New approaches to optical design have resulted in significant improvements in the instrument speed and hence sensitivity, thus lowering the threshold of the intensities of auroral features that can be seen. Thus we will now be able to explore details in what appeared to us previously as "dark" regions. In particular, the progress in vacuum ultraviolet filter design has been major. As a result of being able to fly filters as narrow as 50 Å FWHM, we can now separate the diagnostic spectral features of interest from those that are "contaminants" or obscuring features. As a result, where previously perhaps 60 to 80 percent of the measured signal was contaminant, we now will have 80 to 90 percent of the signal as the feature of interest. This means that we can attempt quantitative interpretation of the auroral information.

X-Ray Imaging. Another new imaging capability that will be employed during the ISTP program will be global x-ray imaging of the auroral zones from high altitudes. An advantage of x-ray imaging is that the intensities and multipoint measurements of the energy spectra of precipitating electrons can be obtained over a broad range of energies as a function of time and position. This technique has previously been demonstrated from balloons and more recently from low-altitude satellites, but it has never been used to image the auroral zones from high altitudes. The Polar satellite will obtain, for the first time, global x-ray images that will complement the imaging in the UV and visible regimes and that will permit detailed studies of the morphology of energetic electron precipitation into the atmosphere during time-dependent events. Continuous measurements will be made over several hours, spanning the typical duration of a substorm.

Three-Dimensional Ion Composition, Charge States, and Fast Plasma. A major new advance, which is included in each of the Earth-orbiting ISTP spacecraft, is the ability to make three-dimensional ion composition measurements at the same time resolution as the electron and total ion measurements, i. e., returning a complete mass-resolved ion distribution function for every spin (and in some cases every half-spin) of the spacecraft. Previous missions have generally obtained only two-dimensional distributions and in most cases required the scanning of ion mass, leading to time resolutions of several spacecraft

spins for even a two-dimensional measurement. Different techniques are used to achieve this new capability in ISTP, e. g., permanent-magnet mass analysis on Polar, electromagnets on Geotail, and time-of-flight analysis on Polar, Cluster, and FAST. The high-time-resolution, three-dimensional ion composition data will provide the needed spatial resolution in the important transition regions such as the cusp and boundary layers and in the auroral acceleration region. It also will allow the current carriers of the ion component of field-aligned currents to be determined as well as the mass dependence and plasma mass density important for ion acceleration mechanisms and wave-particle interactions.

Another major advance is the inclusion of charge state measurements in most of the ISTP spacecraft. This capability will allow the first determination of particle sources throughout the magnetosphere as well as a direct measure of plasma transport throughout the magnetospheric system. The observation of intensity variations as a function of energy, species, and charge state will provide information necessary to unravel the acceleration/energization processes.

Another new capability on Polar will be the ability to sample the loss cone and source cone continuously as the spacecraft spins. In previous missions it has been difficult even to sample the loss cone. The structure within the loss cone must be determined in order to assess the importance of the various proposed particle precipitation processes. This capability will also allow the energy spectra (above the photoemission energy) of upward electron beams, which are important carriers of field-aligned currents, to be measured. In previous missions, such as Dynamics Explorer, only part of the energy spectrum could typically be sampled as the detector scanned through the loss cone, and the total spectrum had to be reconstructed statistically.

Central Data Base and Communications Network

The global and interdisciplinary nature of the problems addressed by ISTP requires both a carefully planned and coordinated set of measurements throughout the geospace system and the establishment of an accessible central data base containing all ISTP data. While elements of these requirements have been met in past programs, the end-to-end planning and implementation in ISTP will result in a major new capability for the space plasma physics community. The core ISTP spacecraft have been planned so that their instrumentation and orbits will optimize both global and local science objectives. To fulfill these objectives the data from the ISTP spacecraft will be made available to researchers through a central data base and communications network. Easy access to an ISTP key parameter (browse) data base and ultimately to high-resolution data is being established.

Incorporation of Theory, Modeling, and Simulation from the Outset of the Program

From the outset, theory and modeling have been fully integrated into ISTP planning. As a result, access to models and simulations will be incorporated into the ISTP data base and simulation codes will be made available to experimenters, greatly improving the timely interaction between experiment and theory. Thus the ISTP program provides a major advance in multipoint, interdisciplinary investigations by establishing the framework for a

new synergism among theory, modeling, and observations. Not only will this framework provide a substantial increase in the rate of progress toward solving ISTP problems, but it will be possible to use experiment-tested model and simulation results as guides to further ISTP observing campaigns.

The ISTP spacecraft will make detailed measurements of the local particles and fields environment. However, the experimentalist will still be faced with the old dilemma of having to deduce from these local measurements what the large-scale structure and dynamics were that produced the local phenomena. Nowhere is this difficulty more severe than in the geospace boundary layers. Even with the ISEE-1 and ISEE-2 satellites, the decoding of space-time and the identification of large-scale behavior were not trivial. The four Cluster spacecraft will improve upon the ISEEs, but here another issue emerges—the ISTP community has little experience interpreting data from four spatially separated satellites, especially when they measure significantly different plasma conditions as will certainly occur in the boundary layer. Simulations could help resolve such problems. Recognizing patterns in the data from either single and/or multiple satellites is the first step toward understanding and interpreting the measurements. Consider a two-dimensional simulation of the magnetopause—perhaps geospace's most complex boundary layer. Although the simulations model only a local piece of the magnetopause, they have the advantage of "knowing" everything that is going on within the simulation domain. Suppose that we place virtual spacecraft in the simulation box, whether at a fixed location or allowing the virtual satellites to move about. We numerically simulate the actual satellite detector responses, create a simulation data set, and process that data through reduction routines similar to those used by the experimentalists. For each of the virtual satellites, we then create a temporal data stream that reflects the complex evolution of the inhomogeneous magnetopause as observed from a local point. The challenge is then to interpret these single-point measurements and to constrict the global dynamics that produced them. Clearly, this exercise is designed to train the eye to take the single-point measurement from virtual spacecraft and see if we can learn to deduce the global structure.

Data-based phenomenological models provide a distillation of satellite measurements taken in various spatial regions under specified geomagnetic conditions. As such, these models summarize in a convenient mathematical form the local physical parameters. Unlike simulations, data-based models do not explain why the physical parameters are what they are, or how these local parameters are causally related to the large-scale dynamics. For the experimentalist who is attempting to explain observations, these models are useful for organizing the data, but do not necessarily illuminate the underlying physics. However, they do provide a benchmark against which to test the simulation models. Let us look at the following example. Assume that we use the well-known model of Tsyanenko for the magnetic field and that there exists another data-based model for E. Then if we know the large-scale B and E fields, we can simply trace particle trajectories through these known B and E fields and construct from these trajectories the Vlasov distribution function. If that computed distribution function matches or agrees in some reasonable way with the measured quantities and yields similar moments as predicted by MHD quantities, then one could conclude with some consistency that a true kinetic simulation of the magnetosphere would result in the same large-scale electromagnetic fields and stresses as obtained by the MHD models. Therefore, these data-based models in conjunction with particle trajectories are necessary to calibrate the MHD models.

IV. SCIENCE TOPICS

The science topics to be addressed by ISTP comprise most of what is interesting and important in space plasma physics. The ISTP goal of understanding the flow of mass, momentum, and energy through the solar-terrestrial system requires that these topics be studied and understood individually and in combination throughout all the elements of the system and particularly at the interfaces between them. Figure 5 is a sketch of the solar-terrestrial environment annotated with various space-plasma processes that will be addressed by ISTP. We note that similar phenomena occur in many regions throughout the system. The investigation of these processes in different environments and over wide ranges of physical parameters is needed for an understanding of the solar-terrestrial system as a whole, but it is also valuable for understanding each individual process.

A. SOLAR PROCESSES

Solar Interior Structure

One of the key scientific objectives of the helioseismology experiments of ISTP is to determine the internal structure of the Sun. This determination will be made by combining measurements of the frequencies of normal modes of oscillations with the development of analytical methods and stellar structure theory. The combination of observations from the instruments SOI-MDI, GOLF, and Virgo on SOHO will allow the determination of the radial stratification and rotationally-symmetric part of the aspheric variation of pressure, density, composition, sound speed, and rotation from the surface to the energy-generating solar core. This procedure will result in a solid foundation in observations to verify stellar evolution models and to understand the physics of the Sun's energy generation.

Most observable oscillations are acoustic waves trapped in a nearly spherical shell. Waves propagating toward the solar interior are refracted toward the surface by the increasing temperature toward the center and are reflected back into the Sun below the photosphere by the sharp decrease in density. Many of the waves live long enough to circle the Sun several times and thus appear as normal modes of oscillation. There are about 10 million trapped modes with measurable amplitudes. The superposition of these modes, each of which has amplitudes at the surface of tens of cm s^{-1} , yields a motion of several hundred meters/second with periods around 5 minutes. The observational task is to separate these modes by their spatial patterns and measure their oscillation periods.

A mode oscillation period depends upon the sound travel time for the path of the wave through the interior. By measuring the frequencies of many modes with slightly different interior paths, the interior structure can be deduced. Since the Sun is nearly spherically symmetric, the surface "shapes" of the mode eigenfunctions are nearly spherical harmonics which are characterized by the integers l and m . The degree " l " is the number of surface node lines, azimuthal order " m " is the number of those node lines that cross the equator. In the radial direction the mode shapes are characterized by the order " n ," which is almost the number of nodes in that direction.

ISTP Science Topics

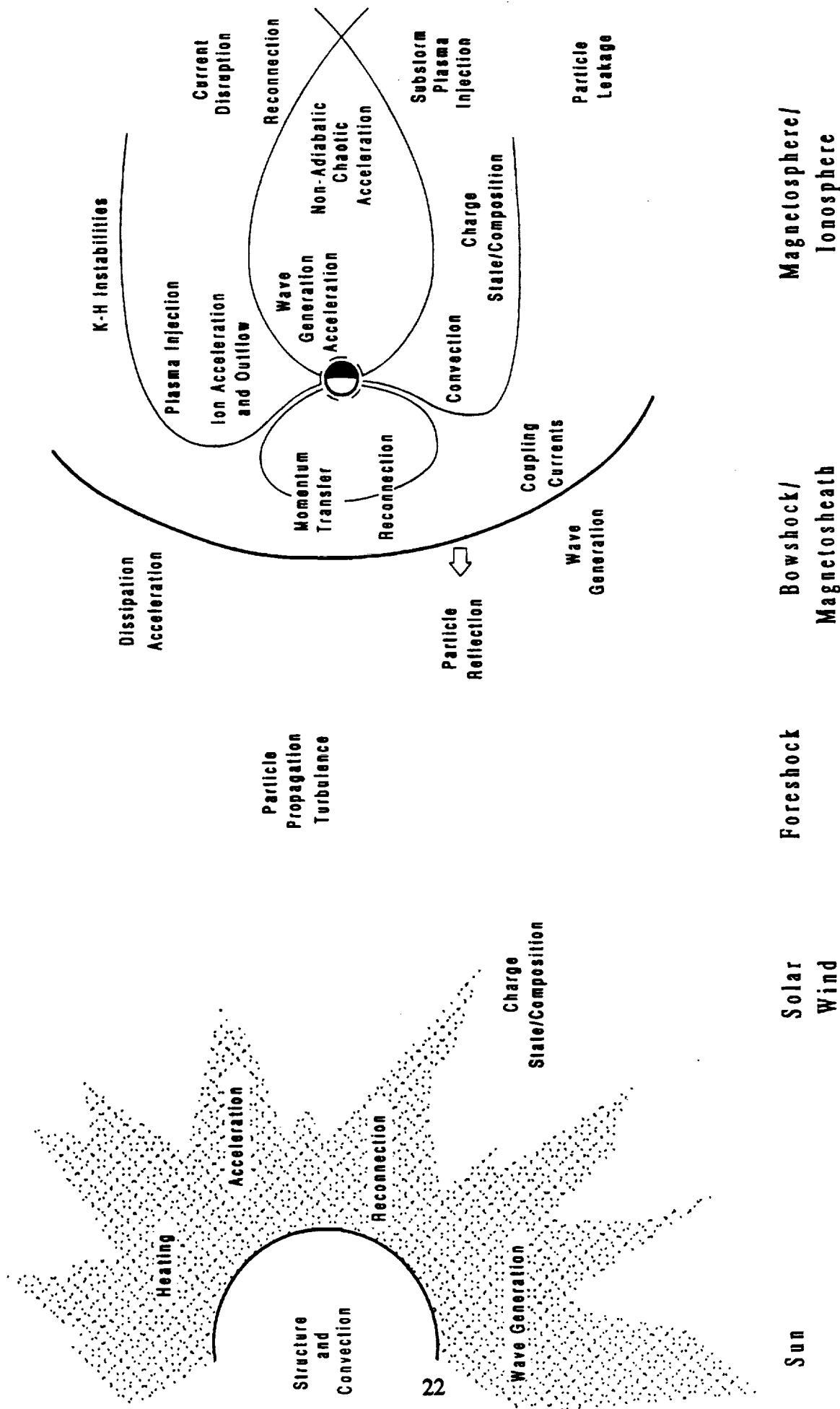


Fig. 5. Sketch indicating the plasma processes that occur in the different regions of the solar-terrestrial system. ISTP's investigation of similar processes occurring in different environments and over wide parameter ranges will advance our understanding both of the system as a whole and of the individual processes.

Modes of low degree penetrate deeper into the interior than modes of high degree. The GOLF and VIRGO experiments measure modes of lowest degree and thus probe the solar core. SOI-MDI will emphasize modes of very high degree and thus will measure the conditions in the outer layers of the Sun. In addition to acoustic or p-modes, there are believed to be buoyancy or g-modes trapped in the solar interior below the convection zone. The detection of some of these modes would greatly enhance our ability to understand the solar core. The prime goal of the low degree measurements is to discover g-modes.

P-mode frequencies change with the level of solar activity. An understanding of these variations will aid in unraveling the processes that drive the solar cycle. The space missions are too short to study these variations fully, but they will allow accurate calibration of the models of the upper atmosphere that are necessary to allow for correct interpretation of longer-duration ground-based observations.

Convection Zone Dynamics: The Source of Solar Activity

In addition to measuring the average structure of the solar interior, SOI-MDI will probe interior convection on all scales from the postulated global-scale giant cells to supergranulation and mesogranulation. In the outermost 30 percent of the Sun the solar luminosity is carried to the surface by convection. This convection is believed to be present at many scales. Global-scale convective motions in both zonal and meridional cells have been postulated from theory and from studies of the long-term evolution of magnetic fields. The global-scale convection and differential rotation are believed to be the driving forces of the solar dynamo, which generates the solar cycle. The characterization of the largest convective motions, with a few to tens of cells across the Sun's surface, will place stringent constraints on models of the solar cycle.

The details of interior motions can be determined by measuring the fine splitting of the frequencies of the p-modes. If the Sun were spherically symmetric, all of the power in each mode would be found in its own spherical harmonic. Interior motions cause perturbations in the trapping cavity, which result in small frequency splittings and shifts of power into several spherical harmonics. The interior convective motions and magnetic fields can be determined by measuring these small power shifts and frequency splittings.

In addition to the characterization of giant-scale convection, the SOI-MDI instrument will allow detailed measurement of convection on the supergranulation and mesogranulation scales. These convective motions result in tens to a thousand cells across the solar diameter. Convective cells of these scales are believed to govern the formation and evolution of solar active regions. While the detailed plasma processes responsible for the development of activity and impulsive energy-release processes will have to await observations made with a spatial resolution only available with OSL, the MDI instrument will be able to measure the gas motions which ultimately drive the process. These observations will be made both by direct measurements of gas velocity and by following the advection of granulation, magnetic, and velocity patterns by correlation tracking.

Using the several million concurrent oscillation modes as probes, SOI-MDI should be able to map the interior structure of magnetic-field regions as well as the interior convective motions. It is now known that there are sufficient interactions between the wave field and magnetic regions to allow detection of magnetic regions by oscillation measurements. This interaction may allow us to predict the development of active regions by detecting the magnetic fields prior to surface eruption.

Magnetic Flux History

The SOI-MDI instrument will obtain a series of magnetic-field maps required for interpretation of the oscillation observations but will have additional important applications. Since these magnetograms will be obtained at a higher cadence and with a more uniform quality than is possible from the ground, they will be a unique source of data on their own. They will allow a detailed study of the magnetic-flux evolution of active regions and the connection between the eruption of magnetic flux in active regions and the formation of the magnetic patterns that apparently govern the large-scale structure of the corona.

Global Mapping of the Solar Wind and IMF

A cooperative effort made possible by simultaneous photospheric magnetic field measurements and the coronal measurements made by SOHO instruments should allow development of a model of the three-dimensional source of the solar wind and interplanetary magnetic field. The large-scale photospheric magnetic field governs the structure of the lower corona. Models of the coronal field based on the observed photospheric field show regions of open fields and regions of locally closed field lines. The open regions correspond to source regions of high-speed solar-wind expansion. The SOI-MDI magnetic field measurements will be used as input to a coronal field model, while the coronal experiments will measure coronal temperatures and density. These data can be combined with the magnetic-field model to generate the first global model of solar-wind generation. Present schedules will allow testing of this model with combined measurements from Wind and the second pass of Ulysses.

Irradiant Flux

The solar outputs of visible, UV, EUV, and x-ray radiations are the primary sources of energy controlling conditions in the terrestrial atmosphere from the troposphere to the lower thermosphere. SOHO will provide direct measurements of spectral irradiance in the visible, and in several regions of the UV and EUV. These measurements, coupled with the high-resolution (spatial and spectral) observations of the solar atmospheric layers where the UV, EUV, and x-ray radiations are generated, will provide information that can be used to model the solar spectral irradiance from the visible to the x-ray portions of the spectrum. The combination of measured and modelled spectral irradiance can be used for studies of the terrestrial atmosphere. Total solar irradiance will be measured by the VIRGO instruments on SOHO with the contributions to the flux from sunspots and plage regions measured by SOI-MDI. The combination should lead to a significant improvement in our understanding of this important input to the terrestrial system.

At a more fundamental level, the solar irradiance, magnetic, and high-resolution observations from SOHO will provide critical empirical information needed to investigate and improve our understanding of the mechanisms responsible for solar variability.

Coronal Heating and Acceleration of the Solar Wind

Knowledge of the physical conditions in the coronal source region of the solar wind is vital to the development of an understanding of the mechanisms that heat the coronal plasma and accelerate it outward to form the solar wind. Instrumentation on the SOHO spacecraft will provide the first detailed measurements of the temperature-density-velocity structure of the coronal source region of the solar wind from the solar surface out to beyond 5 solar radii. In addition, SOHO will provide observations of some structures and transient phenomena out to 30 solar radii. These data will provide critical information for placing empirical constraints on, and insights concerning, the mechanisms for heating and accelerating the coronal plasma.

Because the electron and ion temperatures in the coronal plasma become collisionally decoupled about 0.5 solar radii above the surface, it may be possible to detect signatures of heating processes that preferentially heat different particles (because of charge or charge-to-mass properties) if there is significant plasma heating at these levels, as proposed in some studies.

Although we understand how the solar wind can be accelerated by thermal pressure gradients (Parker-type wind), there is uncertainty as to the mechanism(s) responsible for accelerating the steady-state wind to velocities approximately twice as high as predicted for a thermally driven wind. One possible mechanism is acceleration by Alfvén waves. The SOHO coronal instruments in combination with in situ instrumentation on SOHO and other ISTP spacecraft will provide critical measurements for testing the Alfvén-wave hypothesis. These instruments will also provide critical data for testing other hypotheses proposed for solar-wind acceleration, such as acceleration by magnetic forces, which is the most likely explanation of the observed behavior of coronal mass ejections. It has been suggested that smaller-scale magnetically driven ejections associated with small-scale dynamic events (e.g., small-scale explosive phenomena observed in the chromospheric-coronal transition region) could play a role in accelerating the solar wind.

Thus far we have been dealing with the acceleration of the electron-proton solar-wind plasma. There are also unresolved questions about the heating and acceleration of the heavy ions. Are the heavy ions heated by the same process that heats the electron-proton plasma? How are the heavy ions accelerated in the solar wind? Thermal pressure gradients are incapable of accelerating heavy ions to the speeds observed at 1 AU, but it is likely that wave-particle interactions play a significant role. SOHO will provide the first direct, simultaneous measurements of the velocities of the heavy ions and the electron-proton plasma in the solar-wind acceleration region. These measurements will provide critical empirical information for testing proposed mechanisms (and/or providing insights for alternative mechanisms) for accelerating heavy ions.

As indicated above, magnetic forces are believed to be the primary means of accelerating coronal mass ejections (CME). Acquiring detailed spectroscopic measurements in these transient, moving phenomena will be a challenge. However, if sufficient data are acquired, it will be possible for the first time to determine the role, if any, of thermal pressure gradients in driving CME's. In addition, the detailed high-resolution measurements of the structure of the corona (which is controlled by the structure of the coronal magnetic field and its interaction with the coronal plasma), coupled with measurements of the magnetic fields of the surface, will provide critical insights into the process by which the coronal magnetic fields become unstable and magnetically accelerate the coronal plasma away from the sun to form CME's.

Turbulence in the Solar Wind

Ideally, turbulence should be characterized by the determination of spatial cross-correlation functions or wave-number spectra. With very few exceptions, previous work has used data from single spacecraft to construct *reduced* one-dimensional spectra in wave number. This has been particularly true in the solar wind where such studies have proven valuable in describing the propagation, including diffusion, of energetic solar and galactic cosmic rays. The spectra of magnetic and velocity fluctuations in the solar-wind plasma have been studied to characterize the free-flowing solar wind as a turbulent MHD medium. With four spatially separated measurements, Cluster will enhance our capabilities to determine the three-dimensional structure of the correlation functions; however, in the solar wind the flow speed is of order ten times the Alfvén speed and the correlation length of the fluctuations is of order 10^5 km so that special techniques are needed together with prudent use of the "frozen-in-flux" hypothesis to extract the three-dimensional spectral information.

Two approaches to the problem of deducing wave-number spectra from four or more time series have been investigated; one is to use the Cluster configuration as a *wave telescope*. This technique works best when the amplitudes of the fluctuations are relatively small compared with the mean field. In that situation the four Cluster satellites can be used as a frequency-dependent phased array to obtain the frequency spectrum of waves as well as directional information and mode identification. The second approach employs the determination of the *field-energy distribution function*, $P(\omega, \mathbf{k})$ and is based on power spectral techniques. The essential assumption in this formalism is that the turbulent wave field is both stationary in time and homogeneous in space. The technique is sufficiently general that both electrostatic and electromagnetic modes can be analyzed.

By including magnetic-field, electric-field, and velocity fluctuations in these analyses, the cross-helicity, which measures the degree of Alfvénicity of the fluid fluctuations, and the total fluctuation energy can be characterized at significantly higher spatial and temporal scales than has been heretofore possible. It should be possible to determine the cross-helicity spectrum to wave numbers close to the dissipation range of the turbulence. The spatial structure of the magnetic helicity — the measure of the degree of twist or linkage of magnetic flux tubes — is nearly impossible to ascertain from single-point measurements (although the total magnetic helicity and the reduced magnetic helicity spectrum can be obtained). The Cluster configuration will enable at least part of the high wave-number spectrum to be characterized. The dissipation range of interplanetary turbulence has yet to

be studied in any detail owing to limitations in spatial and temporal resolution of previous missions. For Cluster separations of the order of 1000 km, detailed studies of the high wave-number, high-frequency end of the turbulence spectrum can be conducted. The nature of the wave modes present, their spectra, and variation with decreasing spatial scale will enable us to investigate for the first time the transition from the fluid description of the fluctuations to the kinetic processes that must ultimately control the dissipation range of solar wind fluctuations.

B. GEOSPACE

Bow Shock and Magnetosheath

Owing in large part to the high-time-resolution, dual-spacecraft measurements made with the ISEE and AMPTE missions, as well as to the concurrent development of powerful numerical simulation techniques, considerable progress has been made toward understanding the physics of collisionless shocks. For example, we have come to understand the importance of a process of coherent, near-specular reflection of part of the incident ions as the initiating step in the principal dissipation process at all but the lowest Mach numbers. Moreover, we now recognize the importance of the role of the macroscopic magnetic and electrostatic field structure in the reflection process, as well as in determining much of the electron heating at the shock. Finally—and for solar-terrestrial physics perhaps most importantly—we realize how strongly the nature of dissipation processes (and the resulting magnetosheath properties) depend on the shock geometry and the upstream parameters, especially the angle between the upstream magnetic field and the shock normal.

These earlier studies have shown us that, especially in certain parameter regimes, the structure and the output of collisionless shocks have strong temporal and spatial variability. Moreover, even in parameter regimes where the shock itself may be smooth and steady, strong temporal and spatial variations can be caused by sudden changes in the upstream solar wind, especially the magnetic field. Such changes are common in the solar wind, and these temporal and spatial variations in the nature of the shock (either intrinsic or extrinsic) have important implications for coupling processes at the magnetopause. Unfortunately, our previous spacecraft missions could only hint at the existence of these important temporal and spatial effects but could not really explore them.

Spatial and Temporal Structure in the Shock and Magnetosheath. One of the major advances provided by the Cluster mission is the ability to make simultaneous observations at four spatially separated locations. This capability allows, for the first time, the examination of the local three-dimensional structure of the bow shock. With Cluster we will be able to determine the conditions under which the shock is essentially laminar and one-dimensional, as assumed for most current theoretical and numerical treatments. We will also know under what conditions it might have a corrugated, two-dimensional structure or even a "bumpy," three-dimensional structure.

Similarly, the multipoint observations provided by Cluster will make it possible to assess directly the temporal variability of the shock, including variations in the reflected ion fraction, in the ramp structure, and in the macroscopic electric-field structure. Such

variations appear to be particularly important and probably intrinsic to the shock physics in the quasi-parallel regime (in which the upstream magnetic field is more nearly aligned with the shock normal). Current numerical simulations suggest that shocks in this geometry are not stable but rather undergo a process of cyclic reformation. The Cluster measurements will make it possible to test this important possibility and to examine in detail the general response of the shock to sudden changes in upstream conditions. As just one example, Cluster will be able to probe the shape, size, composition, and other properties of *hot flow anomalies* (HFAs), a class of near-shock events believed to be produced by the shock's transient response to a sudden rotation in the upstream magnetic field.

In order to understand the influence of the shock on the coupling between the solar wind and the magnetosphere, we will determine the extent to which the spatial structure and temporal variability of the shock impose structure on the magnetosheath plasma. Cluster will enable us to determine the three-dimensional scale and evolution of the fluctuations in magnetosheath properties (density, temperature, magnetic field, and flow velocity), with special attention to the region adjacent to the magnetopause. Moreover, with Cluster in the magnetosheath and Wind upstream, it will be possible to see how the bow shock alters the structure of interplanetary discontinuities and upstream turbulence.

Traveling interplanetary discontinuities (TID's) will also be encountered by Wind and Cluster. The evolution of such TID structures can be studied in detail through such multipoint observations. Because they are propagating with the solar-wind flow, the TID structure remains relatively stationary during the measurement time which requires the high-time resolution now provided by Wind and Cluster instrumentation. Wind will access TID structure in its solar-wind state, and Cluster can provide measurements downstream of the bow shock to determine the post-shock evolution of the TID. Four-point measurements within the bow-shock and magnetosheath will also be available, providing information on the evolution of discontinuity structures propagating within the magnetosheath.

Shock Dissipation. In addition to allowing us to discern temporal and spatial structure in the shock and magnetosheath, Cluster will have the capability to make mass-resolved plasma measurements, which will permit us to determine what role different ion species play in shock dissipation. Previous observations suggest that heavy ions in the solar wind are affected differently by the shock than are the protons. These differences will be explored and clarified with the new Cluster instrumentation.

Pre-ISTP work has established the importance of the macroscopic shock magnetic and electric fields for initiating dissipation through gross dispersions in velocity space (e.g., ion reflection), but we have not been able to identify convincingly the plasma instabilities responsible for the redistribution and thermalization of this free energy. The multipoint measurements of Cluster will enable us for the first time to measure the current distribution within the shock layer. This capability will be combined with improved measurements of the macroscopic electric field and plasma waves (especially at low frequencies) and with high-time-resolution measurements of the evolution of three-dimensional velocity-space distributions (with the unprecedented ability to resolve unambiguously heating perpendicular and parallel to the magnetic field). Together, these measurements should

enable us to make a firm identification of the microscopic plasma instabilities operating in and near the shock to redistribute and thermalize the free energy imposed on the distributions by the macroscopic fields.

As an example of the opportunities Cluster will provide for gaining new insight into the microscopic shock processes, we will be able to study with higher temporal resolution and sensitivity the intense, spiky electrostatic fields that have been observed within the shock on numerous crossings. These appear to depend on the electron/ion temperature ratio and may be embedded subshocks or nonlinear manifestations of high-frequency waves within the shock. Cluster will probe their three-dimensional structure and will study their role in the overall dissipation process by searching for correlated effects in the particle distribution functions.

One of the particularly important goals for ISTP in the area of shock physics is to establish how the relevant microscopic instabilities vary with the upstream parameters, especially the Mach number and field orientation. One particular area where ISTP can make an important contribution to this effort is in extending the range of observed Mach numbers to low values. The dayside bow shock, which has hitherto been the primary site of detailed shock studies, presents us with low Mach number conditions only in very rare circumstances and only under conditions of low plasma beta. However, it has been pointed out that along the magnetospheric flanks, the bow shock approaches the Mach angle of the solar-wind flow, and the Mach number of the shock becomes quite low for all values of beta and for all field orientations. While Cluster will not have access to this region, the Geotail spacecraft most likely will make numerous crossings of the flank bow shock. Geotail measurements of the shock properties (including the evolution of the ion distributions, which was not possible with ISEE-3 during its deep-tail excursion) will provide a valuable extension to the dayside bow-shock studies. This is especially true in the area of low-Mach number quasi-parallel shocks, which (because of geometric considerations) are doubly scarce on the dayside.

Foreshock

ISTP will also make it possible to investigate the variety of phenomena observed in the foreshock region involving the interplay of particles, waves, and fields. For example, since the first identification of gyrophase-bunched distribution functions in the solar wind using ISEE satellite data, it has not yet been possible to obtain adequate information about their detailed distribution functions, changes with distance from the shock, or variation across the spatial density gradients that are common in the quasi-parallel shock region; in addition, the relationship of these gyrophase-bunched distributions to the "quasi-isotropic" ion distributions observed in the ion foreshock is unknown. Using the multipoint, multi-instrument observations of the Cluster spacecraft, it will be possible for the first time to resolve these gyrophase-bunched distributions and to determine their spatial evolution as they propagate away from the bow shock. Possible identification of these distributions in heavier ions such as He^{++} will give important supplementary information at a different mass per charge. Development and testing of quantitative models to describe these gyrophase-bunched ion distributions are likely to yield critical information about the formation of the ion foreshock and associated conditions at the bow shock. The evolution

of these unique distributions can also be examined and modeled for circumstances in which the convective flow carries them into the magnetosheath. Coupling between low-frequency waves and gyrophase-bunched ions will act to scatter these ions in addition to the velocity dispersion effect that already contributes to their evolution and decay into uniform, isotropic distributions.

ISTP will thus furnish valuable information about the sources and evolution of particle populations in the foreshock, about the structure of the foreshock, and about the interrelationships among the foreshock, bow shock, magnetosheath, and magnetosphere. It will, moreover, allow us to make inferences about the mechanisms involved in the acceleration of the counterstreaming particles. Detection of a near-isotropic distribution of solar-wind ions, for example, will suggest Fermi acceleration, while strong anisotropies and the presence of magnetospheric ions will point to magnetospheric leakage (perhaps through magnetic merging) or shock-drift acceleration as the underlying mechanism.

In addition to making highly resolved measurements of the distributions of counterstreaming particles in the foreshock regions, the ISTP fields and plasma instruments will make it possible to characterize the properties of the waves arising in association with the counterstreaming particles more thoroughly than on previous missions. Determination of the magnetic and electric variations and in many cases the velocity perturbations in the plasma allow calculations of the Poynting or energy flux of the waves as well as determination of the wave mode and hence the associated generation process. The large amplitudes of the waves in the foreshock region will enable investigations of non-linear phenomena such as wave-wave scattering and wave-steepening.

Dayside Magnetopause and Low-Latitude Boundary Layer

The dayside magnetopause is the site of significant mass, energy, and momentum transfer between the solar wind and the magnetosphere. The transition from the magnetosheath to the magnetosphere has a complicated layered structure, which can include the depletion layer, streaming energetic particle layer, accelerated flow layer, current layer, and Low-Latitude Boundary Layer (LLBL). A number of models, both steady-state and transient, describe the interactions that take place at the magnetopause.

Magnetopause Structure and Dynamics. The candidate steady processes of mass energy and momentum transfer include component and anti-parallel merging and viscous and wave-particle diffusion, whereas the transient processes include Flux Transfer Events (FTEs), magnetopause motion driven by variations in the solar-wind dynamic pressure, impulsive penetration of solar-wind filaments into the magnetosphere, and the Kelvin-Helmholtz instability. Each of these mechanisms predicts specific occurrence patterns and structures to be observed at the magnetopause. An important goal of ISTP is to determine the relative importance of each mechanism, as measured in terms of the mass, energy, and momentum that they transfer to the magnetosphere, as functions of solar-wind conditions and location along the magnetopause. A second, related goal is to determine how the dayside plasma is incorporated in the geospace environment.

Previous studies have shown that at times the magnetopause can be described as a rotational discontinuity, implying that magnetic reconnection occurs. However, many questions about this process remain. Among them are: When and where does merging occur, what initiates it, what is the relationship between steady and sporadic merging, and what is its importance as a plasma source for regions such as the LLBL and as a driver for plasma transport? Other studies have shown that at times the magnetopause can be described as a tangential discontinuity, yet mass, energy, and momentum transfer continue to maintain plasma in the LLBL. While several other steady and impulsive transfer mechanisms, such as diffusion and impulsive penetration, have been suggested, the relative importance of each is unknown.

The LLBL is the more familiar of many plasma layers at the dayside magnetopause. Other layers sunward of the magnetopause include energetic particle, plasma depletion, and magnetosheath boundary layers. These layers have the important property of affecting the magnetosheath plasma and magnetic field incident on the magnetopause, and thus changing the input conditions to the magnetosphere. The characteristics, maintenance, and, indeed, the very existence of these layers for differing solar wind conditions is an important but not very well documented topic.

It is well known that the dayside magnetosphere and its associated plasma layers is intimately coupled to the rest of the magnetosphere; however, the details of this coupling are not well known. It is not enough to identify the manner in which plasma crosses the magnetopause; rather, the evolution of the plasma and the energy and momentum that it carries must be determined. Important topics to be addressed include: the fraction of plasma on open versus closed field lines, the role of wave-particle interactions, the mechanisms for the production of field-aligned currents, the admixture of plasma from other sources, and the evolution of plasma distributions from their entry points..

ISTP has several unique capabilities to address these overall objectives. While initial measurements of the dayside magnetopause region will begin with the launch of Wind, the primary purpose of this spacecraft will be to provide continuous solar-wind monitoring. With the launch of Cluster, the study of the dayside magnetopause will begin in earnest. This suite of spacecraft will provide detailed multipoint measurements of the magnetic and electric fields and unprecedented three-dimensional high-time-resolution composition measurements at the magnetopause. These measurements will 1) distinguish between open and closed magnetic-field topologies by determining the normal component to the magnetic field as well as the tangential component of the electric field expected for reconnection; 2) separate temporal versus spatial structures and thereby determine the thickness and motion of magnetopause layers; 3) define appropriate plasma reference frames such as the de Hoffmann-Teller frame, which may be important for magnetic-merging studies and determine how often the boundary is time-stationary enough for such frames to exist; 4) determine the size, occurrence rates, and flux transferred by FTEs, the amplitude and occurrence rates of pressure pulses and Kelvin-Helmholtz-driven magnetopause motion, and the significance of impulsive penetration; and 5) distinguish between solar-wind and terrestrial plasma sources in the various boundary layers encountered in the magnetopause transition. As the Cluster orbit precesses and the coverage in local time increases, a broad

statistical base of magnetopause crossings will be obtained that will allow the determination of the evolution of the boundary layers with position for a variety of solar-wind conditions. The precession of the Geotail 8x30 R_E orbit to the dayside will contribute low-latitude magnetopause crossings that are missed by the Cluster orbit. (The separation of the LLBL source region from that along the flanks, however, can only be inferred from the location of the measurements and information about the time history of the high-latitude magnetospheric convection. This information will have to come largely from ground-based incoherent radar observations.)

In addition to the use of Wind as a continuous monitor of the solar wind during Cluster and Geotail magnetopause crossings, simultaneous remote observations of the dayside polar cusp from Polar will be highly desirable. These remote observations provide a global measure of the plasma and energy deposition in the cusp region, which is linked to the dayside magnetopause through the LLBL. They also help establish the location, occurrence frequency, and time dependence of transient features in the LLBL that may be encountered by the Cluster spacecraft. There could also be fortuitous occasions when Cluster is in the magnetosheath or upstream solar wind and can be used as a near-Earth solar wind monitor for Geotail observations of the equatorial magnetopause.

Magnetopause Thickness. Most observations of the magnetopause region have been made with only one spacecraft, which results in a basic ambiguity between space and time variations for time-series measurements. Although Wind and Polar will provide samples of the magnetopause and boundary at various local times and latitudes and can be used to obtain estimates of magnetopause to boundary layer thickness ratio, only the multi-spacecraft Cluster mission can provide absolute thickness estimates. Corrections can be made for boundary waves and other three-dimensional effects in addition to separating the basic time and space variations through its multipoint measurements. Estimates to date for magnetopause thickness range from less than 100 km to more than 1000 km and there continues to be large uncertainties in observed ratios of magnetopause to boundary layer thickness although these measurements are critical for testing competing models for the generation of the magnetopause and boundary layer such as shear-driven MHD instabilities and reconnection.

MHD Instabilities. MHD instabilities in a collisionless plasma are just beginning to be examined at scales at or below ion gyroradii. MHD instabilities are thought to be important in many space-plasma regions, especially near plasma boundary layers. The presence of shear-driven instabilities (Kelvin-Helmholtz in the linear regime) near the magnetopause and in the magnetospheric boundary layers is especially important due to their potential influence on global magnetospheric dynamics.

Recent simulations of shear-driven instabilities in the boundary layer show the generation of vortex structures and a complex spectrum of large-scale waves near the magnetopause along with field-aligned currents that can couple into the ionosphere. Multisatellite, multi-instrument measurements, provided especially by the Cluster spacecraft, will make possible detailed tests of shear-driven instability simulations at both MHD and kinetic scale, the latter capability being a fundamental advance over all previous

space plasma physics experiments. Measurements, along with the theory and simulations to be tested, will include multicomponent plasma effects combined with MHD and kinetic-scale measurements, from very-low-frequency magnetic fluctuations to high-frequency electric fluctuations, providing the capability to separate out the effects of wave-particle coupling.

For special conjunctions of Cluster in the LLBL, with Polar or other spacecraft in the cusp region, effects in the cusp region linked via the geomagnetic field to the region of active shear-driven instability near the magnetopause can be directly tested in terms both of the generated electric current and of associated particle distributions and plasma waves that propagate along the connected flux tubes. With these powerful new tools, basic plasma-physical processes can be examined along with the interplay between kinetic and MHD scales. In addition, cusp-region and ground-based observations linked to the simultaneous boundary-layer measurements can help to determine both the coupling process between these regions and the relative contribution of boundary-layer processes to the low-altitude cusp region and the global electrical circuit.

Magnetopause Microstructure and Boundary Conditions. Specifying appropriate boundary conditions for the magnetospheric system is fundamental to developing a quantitative and predictive model. The magnetopause is a prime example of an MHD discontinuity in a collisionless plasma. Previous observations of the magnetopause region are mostly one-point measurements, which contain space-time ambiguities in time-series data. The two ISEE spacecraft provided some limited two-point measurements yielding observational constraints along the interspacecraft line; but most two-spacecraft studies from ISEE have focused only on magnetic-field variations. Multipoint plasma measurements have proven to be much more difficult without more built-in coordination. ISTP provides coordinated multipoint observations with significant built-in portability and comparability of multiple plasmas and fields data sets.

Using a suite of four similarly instrumented spacecraft and variable interspacecraft distances from less than gyroradii scale up to the scale of maximum boundary-layer thickness, Cluster will make possible a detailed plasma, field, plasma-wave, energetic-particle, and ion-composition specification of magnetopause microstructure. The multipoint observations can unfold a combination of boundary movements, waves on the magnetopause boundary, layered structures at or near the magnetopause, and space-time variations. All of these effects have led to difficult ambiguities in previous studies. Cluster will isolate and correct for such effects and thus make possible a major advance in studies of magnetopause microstructure. In particular, electric-field and plasma measurements will allow a unique specification of the de Hoffman-Teller frame appropriate for each specific boundary crossing. Then, simultaneous upstream-downstream particle and field measurements will provide inputs to computer simulations of detailed discontinuity structure. Comparisons of the four-point Cluster observations will allow corrections for the effects noted above in order to re-order the observations in a coordinate system and parameter space best suited for testing the theory (e.g., of tangential or rotational discontinuities) and model simulation in three dimensions. Applying such methods to a representative set of magnetopause crossings in different locations and under different

conditions of the solar wind and magnetosheath plasma and field source will lead to a specification of the distribution of the normal magnetic-field component at the magnetopause, a key boundary condition for global magnetospheric models.

Ion-composition, charge-state, plasma-wave, and energetic-particle observations performed simultaneously will provide quantitative testing of discontinuity models at various stages of development from one-dimensional and two-dimensional hybrid simulations up to full three-dimensional, multicomponent kinetic simulations. Detailed tests of kinetic plasma instabilities will also be performed, including conditions for lower-hybrid drift instabilities and other drift modes considered applicable to this high-gradient region. The interplay between kinetic and MHD processes will be revealed through successive tests of both kinetic and MHD models applied, in a complementary way, to understanding magnetopause microstructure.

Cusp

Although there have been some measurements in the exterior cusp region near the magnetopause, this region remains poorly explored. The cusp is believed to be an important site of magnetosheath plasma entry into the magnetosphere through a variety of processes, including direct plasma entry, plasma diffusion, and reconnection. All of these processes have distinct signatures, greatly affect the relative importance of the magnetosheath plasma entry, and have consequences on the ultimate fate of cusp plasma. Since these processes are not necessarily mutually exclusive and are likely to be dependent on solar-wind conditions, a large data base of cusp crossings is needed.

In addition to being an important point of entry for solar-wind plasma, the cusp region has been more recently recognized as a region where dissipation of solar-wind energy from currents and particle precipitation leads to large localized H^+ and O^+ ion outflows. These ion flows are transported back over the polar cap through the magnetotail lobes and eventually into the plasma sheet. Their point of entry into the plasma sheet is determined by the magnitude and direction of the polar-cap convection. Typical distances inferred from limited particle trajectory modeling are 10 R_E downtail for O^+ for active convection and 25 R_E for quiet convection conditions. Correspondingly, the ionospheric H^+ from the cusp has higher field-aligned speeds as compared to the convection velocity and travels farther down the magnetotail to distances of greater than 25 R_E before it reaches the midplane of the magnetotail and can enter the plasma sheet. This is also true for the solar-wind ions, principally H^+ and He^{++} , whose still higher field-aligned velocities make entry to the plasma sheet difficult except at distances exceeding 50 R_E . Some plasma will also be lost down the tail.

Thus, in addition to identifying the entry processes, determination of the evolution of cusp plasma is of critical importance in characterizing the cusp and understanding how this region is connected to the larger magnetospheric system. Some of the significant questions that should be addressed are: How does plasma convect through the cusp? How does ionospheric plasma in the mid-altitude cusp convect to other regions? How does this convection depend on solar-wind conditions? By addressing these questions and others,

both the characteristics of the cusp and its connections to adjacent plasma regions such as the plasma mantle and LLBL will be determined.

One of the primary objectives of ISTP is to develop a clear understanding of the entire cusp region. The Polar spacecraft will make measurements in the mid-altitude cusp. Detailed measurements of the electric and magnetic fields in the cusp will allow the determination of cusp currents. Coupling these measurements with three-dimensional composition measurements and UV and x-ray images will allow the determination of plasma sources, sinks, and transport throughout the mid-altitude cusp. Coupled with Wind measurements upstream, a nearly complete accounting of the variations of these quantities with different solar-wind conditions will be made.

With the launch of the FAST spacecraft, high-time-resolution measurements of the low-altitude cusp and correlative studies with Polar of the low- and mid-altitude cusp will provide important information on the plasma transport through this region. With the launch of Cluster, exploratory measurements of the exterior cusp/entry-layer region will be made. The question of how the plasma seen at Polar altitudes enters the cusp region will be addressed by detailed measurements of the plasma composition and dynamics and of the magnetic and electric fields in the exterior cusp region. The important coupling of this region with the LLBL and the plasma mantle will be accomplished by these same measurements. Fortuitous occurrences when both Polar and Cluster are in the cusp will extend the Polar and FAST correlative studies of the cusp from low altitudes out to the cusp-magnetosheath interface.

In addition to the use of Wind as an upstream monitor, there will be many opportunities to use Cluster as a near-Earth plasma monitor when it is located in the magnetosheath or upstream solar wind and Polar is located in the cusp. These opportunities are critical to the understanding of the relative mix of solar and terrestrial plasma in the cusp. By combining the exploratory measurements of Cluster in the exterior cusp with Polar, FAST, and Wind observations, the sources, sinks, and transport of plasma through the cusp and the coupling of this important plasma region with the rest of the magnetospheric system will be established.

The study of the cusp region, especially the cusp-magnetosheath interface, is largely exploratory. The composition and charge-state measurements in this region will provide unique tests of quantitative models for plasma sources, sinks, and transport that were not previously possible. In particular, development and tests can be made of two-dimensional and three-dimensional MHD simulations of the region. This will lead to a deeper understanding of the entire cusp region, which is not possible with observations alone. The exploratory nature of the measurements and the interplay between new observations and theory make the cusp one of several regions where there will be many surprises in store and where the anticipated results from the ISTP mission are difficult to quantify.

Plasma Mantle

The plasma mantle serves both as a point of entry for solar-wind plasma and as a reservoir for the polar-wind H^+ and He^+ flows from the ionosphere. The mantle, especially the high-

latitude boundary layer portion, is relatively unexplored and will remain so even after ISTP, except for some near-Earth sampling that can be carried out by the Polar spacecraft and occasional measurements from Cluster. Diffusive entry of solar-wind plasma is thought to occur in this region in a non-localized fashion as opposed to the localized entry through the cusp region. As such it will not show the signature of mass/velocity filtering that the cusp sources will and which can be observed by Geotail as mass layering in the magnetotail lobes with the lower-mass, higher-velocity ions nearer the magnetopause boundary and the higher-mass, lower-velocity ions nearer the central magnetotail axis. This large geomagnetic mass spectrometer is formed as a result of the localized cusp entry point and the near equal ion energies of the separate ionospheric (~ 10 eV) and solar-wind (~ 1000 eV) ion populations. In contrast, the dispersed entry of the polar-wind ionospheric and high-latitude boundary-layer solar-wind ions in the mantle will lead to a diffuse background of H^+ , He^{++} , and He^+ in the magnetotail lobes with energies between 1 and >1000 eV. The subsequent entry of this plasma into the plasma sheet will depend on the point of magnetopause entry along the magnetotail axis, the velocity of the ions, and the magnitude and direction of magnetospheric convection. The larger velocities of the solar-wind ions will generally result in a plasma-sheet entry in the deep tail or loss down the tail. This tendency is further amplified by the $-x$ (GSM) position of entry at high latitudes.

Among the questions that Geotail measurements, in combination with data from other ISTP spacecraft, will allow us to answer are: What is the ratio of solar wind to ionospheric plasma in the mantle as functions of solar-wind parameters and the state and phase of magnetospheric activity? What are the relative sizes of the cusp and the "open window" as portals through which magnetosheath plasma enters the mantle? What is the total flux of mass, momentum, and energy through the mantle as a function of solar wind parameters and the state and phase of magnetospheric activity? What is the loss of mass, momentum, and energy flux from the mantle to the magnetosphere? Can the mantle be a major player in the magnetosphere's mass, momentum and energy budget, as postulated in one main model?

Composition measurements on Geotail must be interpreted in terms of the relative ionospheric and solar-wind contributions. For this purpose, the data must be normalized using solar-wind composition measurements from Wind. Success will have been achieved when we are able to make a defensible, empirically-based statement of the form: The plasma mantle is dominantly (certain percentage) solar-wind plasma; the percentage of ionospheric plasma varies from ? to ?, the amount depending on the state and phase of magnetospheric activity, solar-wind conditions, and the solar EUV flux.

Mantle data from Geotail must be combined with cusp data from Polar to compare the strength of the cusp as a source for the mantle against the strength needed to supply the observed mantle. Success will take the form of a statement to the effect that the cusp is adequate or inadequate to supply the mantle.

Mantle data from Geotail must be combined with solar-wind direction determinations from Wind (to fix the position of Geotail within the tail's cross section) to build up cross-sectional contour maps of mass, momentum, and energy fluxes within the mantle, binned

according to IMF quadrants. Success will take the form of such contour maps from which the total fluxes can be determined.

Mantle data from Geotail must be compared with magnetosheath data from the flanks (from IMP 8 measurements or inferred from Wind solar-wind data) to look for slowing relative to the predictions of appropriate dynamical models for mantle flow. Success will take the form of a definitive detection of slowing. The value of the result will be greater if a reliable quantification of the amount of slowing is obtained.

Origins of the Magnetospheric Coupling Currents

To drive magnetospheric convection, Region 1 currents convey energy from the boundary to the ionosphere, which then distributes it throughout the closed field line volume via Region 2 currents. A major question relating to these currents is, where do they originate? The options are the low-latitude boundary layer, the high-latitude boundary layer, and the plasma-sheet boundary layer. To develop a quantitative model of magnetospheric convection, it is essential to answer this question.

Moreover, cusp/mantle currents are not greatly inferior to Region 1 currents in strength, yet no model explains their source or function in a way that accounts for all of even their main features.

To address the first question, the plasma analyzer on Polar will be used to measure the Region 1 current density directly, and thereby, over the course of a year, to build up a contour map at mid-altitudes. This will help discriminate between low-latitude and plasma-sheet-boundary-layer sources. Cluster and Geotail measurements in the low-latitude and plasma-sheet boundary layers will be used to build up regional magnetic field maps. These can be compared with theoretically derived maps based on each layer as the source. The magnetic signature of the source will be quite apparent when exposed in this way. Success will occur when the source has been unambiguously identified.

To address the second issue, regional magnetic field maps from Cluster will be used to infer the presence of field-aligned currents and their relationship to boundary structures and processes. Success will be achieved when the source and cause of cusp/mantle currents has been identified.

The Plasma Sheet

The plasma sheet is a great reservoir of hot plasma for the magnetosphere. It is populated both by solar-wind plasma, which enters through the various boundary layers, and by plasma that escapes from the ionosphere along magnetic lines of force. Its boundary, the plasma sheet boundary layer (PSBL), with the nearly empty magnetotail lobes, is known to contain intense ion and electron beams and field-aligned currents, showing it to be both an important particle transport region and a major current-carrying region presumably connected to the ionospheric current system. Along with these important attributes, the PSBL contains intense wave populations and sharply peaked electric fields, indicating that it may also be an important particle energization region. ISTP, with its composition, charge state, wave, and field measurements, will be able to determine source mixing and transport

through the plasma sheet and to determine the effectiveness of PSBL particle energization processes.

Sources, Loss, and Transport of Plasma Sheet Plasma. Although much has been learned from earlier programs about the strengths and characteristics of both the solar-wind and ionospheric sources in the cusp, almost nothing is known about the transport, entry, and mixing of this plasma in the plasma sheet. The early part of the ISTP mission, when Geotail is still in the deep tail, will be particularly useful for examining this problem. Wind will characterize well the solar wind, including composition and charge state. Polar's complement of low- and high-energy ion mass spectrometers is well suited for characterizing the source strength in the cusp and polar cap; of crucial importance, too, is Polar's ability to negate the positive charging of the satellite that otherwise would make low-energy flows difficult to observe. Geotail is also well instrumented to observe the relevant particle populations and will be positioned to observe the ion flows as they are energized, convect down the tail, and eventually enter the plasma sheet.

Another region of significant importance in supplying the plasma-sheet population is the nightside auroral zone. Large fluxes of H^+ , He^+ , and O^+ ions with characteristic energies of a few hundred to a few thousand eV have been observed to flow out of the auroral oval during magnetically disturbed conditions. The relatively large velocities and the fact that these ionospheric outflows originate on magnetic field lines connected to the plasma sheet mean that this ion source region has direct access to the plasma sheet. However, the distribution of this source with respect to the downtail distance is highly uncertain and is not likely to be well understood without the inclusion of the Equator spacecraft. The Polar spacecraft, on the other hand, should do an excellent job of measuring and further quantifying the strength of the auroral ion source. At still lower altitudes, near the ionospheric source, the FAST spacecraft will make very high temporal/spatial resolution measurements of the process that extracts the ions.

A major objective of ISTP is to determine the relative contributions of the ionospheric and solar-wind sources to the plasma sheet as a function of dynamic conditions. This will require ion-composition, charge state, and phase-space-distribution information from all core ISTP spacecraft including Polar, Wind, Geotail, and Cluster. Ion-composition and charge state data will provide the primary means of distinguishing the ionospheric and solar-wind origin of the plasma. Phase-space-distribution data, in conjunction with spatial location and time history of magnetospheric convection, will be the primary means of distinguishing the regions and processes that play a role in plasma-sheet formation. Since the source strengths and the transport via magnetospheric convection vary with the dynamic state of the magnetosphere, sampling will be done under both active and quiet conditions. Since the ISTP mission will take place during solar minimum and the relative source strengths are known to be solar-cycle-dependent, further understanding of this long-term dependence will require comparison with previous missions.

The loss of plasma from the plasma sheet is strongly linked to the dynamics of the plasma sheet; active and quiet conditions are expected to create two very different scenarios. During quiet conditions, steady loss down the tail is expected and should be

observed by Geotail. In addition, non-adiabatic and chaotic energization of ions near the neutral sheet are expected to generate earthward-streaming ions, some of which can eventually precipitate into the Earth's atmosphere. Some theories predict that the location of the expected maximum precipitation zones will be in regions of chaotic acceleration, which depends on a resonance between the ion-bounce motion across the neutral sheet and the ion-cyclotron motion. Hence, the relative location of these regions within the magnetotail will depend on the species through the cyclotron motion and the tail magnetic-field structure. The downtail distance of the chaos zones will map into a latitude dependence of ion precipitation in the auroral zone; this dependence should be readily observable by the Polar ion mass spectrometers. Furthermore, Geotail and Cluster should be able to make occasional *in situ* measurements of the fields and plasmas in the regions near the neutral sheet where the acceleration occurs.

The situation is expected to be quite different during substorms. Although the quiet-time loss mechanisms should still be active, they are likely to be less important than other processes. Of primary interest will be the observation of plasmoid formation and its subsequent ejection down the tail during the substorm expansion and recovery phases. Determining the composition of the plasmoid as a function of downtail distance may well provide insight into the mechanism for plasmoid formation. Composition measurements are also expected to play a key role in understanding the re-creation of the plasma sheet during the late recovery phases.

Wave Activity and Fields in the Plasma Sheet and Plasma Sheet Boundary Layer. Geotail and Cluster instrumentation will provide the data required to determine the dominant wave modes, including wavelengths and polarizations, and the nature and structure of the spiky electric fields that have been observed in the plasma sheet boundary layer (PSBL).

ISTP data will also permit us to investigate wave-particle interactions and to evaluate various proposed mechanisms for particle heating and acceleration. Current sheet acceleration, acceleration in the electric field at the neutral line, acceleration in waves at the PSBL, heating by waves in the PSBL, and acceleration by parallel electric fields in the PSBL have all been studied experimentally and theoretically by utilizing data from previous satellites. The relative importance (and, in some cases, even the existence) of the various mechanisms during quiet and active times has not been definitively determined. ISTP's high-time-resolution plasma-and-fields data and, in particular, the new capability to have high-time-resolution, mass-resolved three-dimensional ion data will allow us to distinguish among different mechanisms, determine their relative importance, and, therefore, decide which of the competing theories are most valid.

ISTP will also make it possible to study the MHD structure of the PSBL. Although much work has been done on the MHD structure of the bow shock and the magnetopause, very little similar work has been done on the PSBL. Evidence has been presented that the boundary (deep tail) or a part of the boundary (near tail) is a slow-mode shock. The Cluster data in the near tail and Geotail in the far tail will make possible a determination of whether slow-mode shocks are a persistent feature at the lobe/plasma-sheet interface, which is critical to an understanding of the reconnection process in the magnetotail.

Magnetospheric Substorms and the Magnetotail

The flow of mass, momentum, and energy through the geospace system, which is a central theme of the ISTP program, is characterized by a more-or-less continual process of accumulation of solar-wind energy by the Earth; this process is punctuated by intermittent sudden releases, with a more-or-less constant "average" amount of plasma being retained by the Earth. The sporadic releases of plasma by the magnetotail are manifested by a set of phenomena occurring throughout the magnetosphere which, taken together, constitute a *magnetospheric substorm*. At the Earth itself, a signature of the substorm is the *auroral substorm*, which consists of a characteristic brightening and configuration change of the auroras.

Configurational changes of the magnetosphere during substorms. A leading model for the magnetospheric substorm invokes net transfers of magnetic flux, see-saw fashion, between the dayside magnetosphere and the tail: the tailward swing is the growth phase; the sunward swing, the expansion phase. Tailward transfer expands the boundary of the tail and contracts the dayside boundary. Further, tailward transfer expands the polar cap while sunward transfer contracts it. This model needs to be tested, and the relative motions of each component quantified empirically. The result will be a magnetic flux budget for the substorm life cycle, showing the changes in dayside flux, closed nightside flux, and open tail flux as functions of substorm phase.

Data from ISTP spacecraft will be required to work out the magnetic flux budget for the substorm cycle. Solar-wind pressure data from Wind will be used to normalize magnetospheric boundary positions to a standard value. Cluster will fix the position of the dayside boundary, while Geotail determines the tail boundary. Polar will be used to determine the size of the polar cap, while FAST is employed to determine the transpolar voltage and to measure the Region 1 currents. Success will take the form of determining the incremental changes in dayside and tail boundary positions corresponding to changes in polar cap size for fixed solar-wind pressure. This, together with the transpolar voltage, will make possible the construction of a magnetic flux budget for the substorm.

Physical Processes Leading to the Expansion Phase. The coupling of solar-wind flow into the magnetosphere becomes more efficient as the interplanetary magnetic field (IMF) southward component increases. The substorm *growth phase*, mentioned above, is the collective name for the gradually increasing energy dissipation processes that are manifested by many observables and at many venues throughout the magnetosphere and ionosphere. These *directly-driven* phenomena will no doubt be the first that we are able to understand quantitatively, and the configurational changes described above as tailward swings are their direct result.

The substorm *expansion phase*, which involves the explosive release of energy stored within the magnetotail during the growth phase, poses a more difficult problem. Several important models have been proposed to explain what happens at and after expansion phase onset. Some of these models are complementary, while others are contradictory, and future progress demands that we address them definitively. As with energy transfer at the

magnetopause, both reconnection and Kelvin-Helmholtz instabilities are involved in different expansion-phase constructs.

The concept that the neutral-sheet current, which helps maintain the stretched-out field lines of the magnetotail, is disrupted as the expansion phase begins, has been very useful in explaining the "sunward-swing" configurational changes and the flow of field-aligned currents into the nightside ionosphere. This concept can be complementary to different expansion-phase models because the current disruption may result from several different mechanisms within the magnetotail, such as reconnection or anomalous resistivity.

Another concept that can be applied to different expansion phase mechanisms is known as the *thermal catastrophe model*. In this model, the expansion phase is triggered by a rapid increase of Alfvén wave dissipation in the PSBL. Low-frequency waves are first excited along the magnetopause and reach an Alfvén resonance condition as they propagate through the magnetotail lobes and reach the PSBL. Ultimately, the release of stored magnetotail energy must be initiated by whatever process may be triggered by the resonant wave energy, and reconnection is certainly a leading candidate.

For many years, attention has been focused on neutral-sheet tearing instabilities for initiation of reconnection in the magnetotail. Both resistive tearing, involving anomalous resistivity, and collisionless ion tearing have been studied extensively. Questions relating to the stabilizing influence of the more adiabatic electrons, the possible effects of chaotic ion trajectories, the influence of small north-south and east-west components of the magnetic field, and the effects of pressure and temperature anisotropies are being addressed extensively. The higher-resolution multipoint measurements of ISTP are clearly needed for the ultimate resolution of this important problem.

Near-Earth Reconnection Model. Assuming that reconnection is initiated in the magnetotail at the onset of the expansion phase, there are many questions about its location and the evolution of magnetotail structure as substorms grow and then recover. The near-Earth reconnection model for the substorm sequence has endured for over a decade and makes a number of predictions that can be tested by ISTP. This model of the substorm process as it occurs in the magnetotail is depicted in the sequence in Figure 6, which sketches the changes of the plasma sheet and closely neighboring lobe field lines out to a distance of about $100 R_E$ from Earth. The pre-substorm configuration of the plasma sheet (panel 1) comprises a thick plasma sheet with a "distant neutral line" at $\sim 100 R_E$. This configuration begins to change during the growth phase, when the field lines become more stretched in the near-tail and a neutral line forms within the thinning plasma sheet (panel 2), marking the onset of the *expansion phase* of the substorm. Thereafter, magnetic reconnection at this *substorm neutral line* proceeds, severing the closed field lines of the plasma sheet and forming closed loops, which move tailward, and shorter closed field lines, which contract earthward.

Within a few minutes all of the closed field lines of the pre-substorm plasma sheet have been reconnected and lobe field lines begin to reconnect (panel 6). At this time the structure of closed loops, called a "plasmoid," that has been created between the substorm neutral

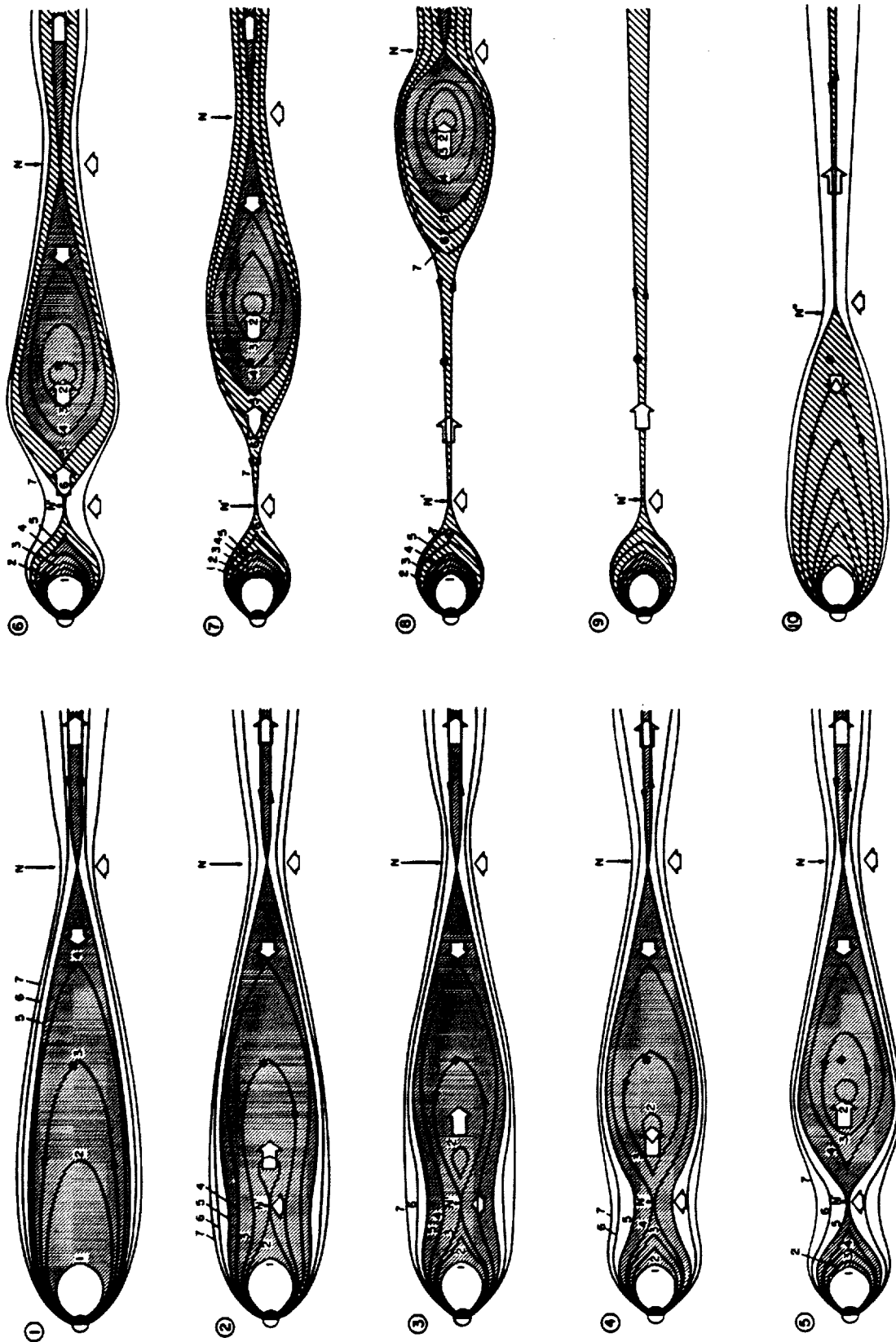


Fig. 6. Sequence depicting the substorm process and plasmoid formation as described in the near-Earth reconnection model. The different panels show the changes that occur in the plasma sheet and closely neighboring lobe field lines out to a distance of about 100 RE from Earth. The plasmoid travels very large distances (220 RE) downward, displacing the lobe field outward and producing transient lobe magnetic field variations. These variations provide evidence for plasmoid passages even though the observing spacecraft does not actually enter the plasmoid itself.

line and the distant neutral line is no longer magnetically restrained by the Earth. The plasma pressure gradient and the tension of the sheath of newly reconnected lobe field lines accelerate the plasmoid down-tail to speeds greater than the solar-wind speed; it eventually joins the solar wind and departs the geospace environment. As the plasmoid flows away, the shortened, closed field lines contract back toward Earth (e.g., panel 6). The actions depicted here in the midnight meridian plane actually spread east and west across the tail, so, at off-center locations, the same actions would occur but delayed by a few minutes compared to the midnight meridian. The coarsely-hatched region (in panels 6 and later) contains lobe field lines that reconnected after the plasmoid began its departure and that thus became interplanetary field lines. As noted above, this sheath of interplanetary field lines contracts tailward, helping to accelerate the plasmoid. At large tail distances (e.g., in ISEE-3 measurements at $220 R_E$), the plasma sheet boundary layer is made up of the velocity-dispersed energetic ions and electrons that this sheath contains. As the plasmoid moves down the tail (panels 7 and 8 of Figure 6), the large body of plasma flowing along the midplane displaces and compresses the lobe field, producing an effect called a traveling compression region (TCR) that is easily detectable in lobe field measurements as a northward-then-southward tilting and a compression of the field.

After the plasmoid departs, the substorm neutral line remains near the Earth for another half hour or more, during which time the plasma sheet tailward of it remains very thin and comprises plasma and energetic particles streaming rapidly tailward, threaded by southward-inclined magnetic fields (Figure 6, panels 9 and 10). This is referred to as the "thin downstream plasma sheet." Measurements suggest that its thickness may be no more than 1000 km.

Perhaps an hour after the plasmoid's departure the substorm neutral line moves tailward. Plasma jetting earthward from the retreating neutral line starts to re-fill the plasma sheet. After some further time the substorm neutral line retreats as far as $\sim 100 R_E$, replacing the original distant neutral line and the plasma sheet regains its pre-substorm character.

Other important processes occur Earthward of the neutral line as the plasmoid formed and moved tailward. The Earthward contraction of shortened closed field lines, first the old plasma sheet field lines and later reconnected lobe field lines, projects plasma into the inner magnetosphere, i.e., to geosynchronous orbit and deeper, causing, among other things, a build-up of the ring current and precipitation of particles into the polar ionosphere, creating the auroral substorm.

The Boundary-Layer Model. The boundary-layer model of substorms also involves reconnection, but at a location farther down the magnetotail without the spontaneous formation of an additional, near-Earth neutral line. At expansion onset, the reconnection rate simply increases rapidly, causing a sharp rise in the rate of sunward-flowing plasma, which mirrors near Earth and leads to the counterstreaming ion flows observed in the PSBL. A pre-existing boundary between the antisunward-flowing plasma of the LLBL and the sunward-flowing plasma then becomes the site of Kelvin-Helmholtz instability. This same velocity shear creates field-aligned currents coupling the region to the auroral

ionosphere and particularly to the westward-traveling surges that often appear during substorms.

Observations available to date cannot easily provide a definitive test between the near-Earth neutral line model and the boundary layer model because the reconnection site itself is spatially and temporally localized and single-point spacecraft measurements lead to various ambiguities in uniquely identifying sources and transport processes. Various other substorm models have proliferated, including the wave-induced precipitation model, the current disruption model, the configurational instability model, the magnetosphere-ionosphere coupling model, the thermal catastrophe model, and a recent synthesis model. Providing clear and definitive tests between the near-Earth reconnection model and these various alternative models will require improved magnetic-field mapping techniques, simultaneous coverage of both the distant and near magnetotail, and comprehensive plasma, wave, and DC field measurements, all of which are designed into the ISTP program.

The Role of Waves and Electric Fields in Substorm Dynamics. Several theories of reconnection require the existence of waves to provide dissipation in the collisionless plasma of the magnetotail. ISEE electric-field data provided evidence that lower-hybrid drift waves of sufficient amplitude occurred near the neutral sheet for one event that was identified (from the quasi-static electric and magnetic field data) as the formation of a neutral line earthward of the spacecraft at substorm onset and its subsequent propagation tailward. Due to the limited size of the burst memory and the limited coverage in the mode obtaining low-frequency wave form data, only one event of this type has been identified. In other theories, intense electromagnetic whistler waves scatter the electrons or the existence of chaotic orbits insures that the electrons are demagnetized so that tearing mode reconnection can occur. The electric field and wave experiments on Cluster and Geotail will provide the required time resolution, sensitivity, and time coverage to determine the importance of lower hybrid drift waves and other low-frequency waves in reconnection and answer questions as to when the waves become unstable in a substorm, the saturation amplitudes and mechanisms and the effects on the particles, the effects of ion composition, what percentage of the time they provide the dominant source of dissipation.

The three-dimensional structure and amplitude of the quasi-static electric field in association with substorms must be determined in order to understand the reconnection process and particle acceleration near the neutral line. ISEE data have shown that electric fields up to 40mV/m occur in a class of events that are identified as the formation of the neutral line earthward of the spacecraft. Comparison with the average cross-polar-cap potential implies that the field is primarily inductive. By utilizing the Cluster electric field and magnetic field instruments, the structure of the electric field associated with the neutral line, the propagation speed of the neutral line, and the relative importance of potential and inductive fields can be determined. In addition, by utilizing simultaneous measurements from Cluster near the substorm neutral line and Polar or FAST, direct comparisons between the input solar-wind energy, the cross-polar-cap potential, and the cross-tail potential drop can be made to characterize the flow of energy from the solar wind through the magnetospheric system.

Properties of the Quiescent Magnetotail

The properties of the magnetotail during intervals of geomagnetic activity have been the subject of intense interest. In contrast, the nature of the magnetotail during periods of geomagnetic calm are much less well known. Such intervals might be described as a baseline for the periods of geomagnetic activity, i.e., as intervals during which all the dramatic phenomena observed during active periods have ceased. However, it is important to recall that many as yet undescribed processes may take place only during periods of geomagnetic quiescence or may be more readily detectable at these times.

The fundamental nature of studying the quiescent magnetotail is exemplified by the results of recent studies that show that for distances $< 22R_E$ the plasma sheet ion and electron populations during magnetically quiet periods are well represented analytically by the kappa distribution. They are decidedly not Maxwellian! Not only does this provide a basic insight into the steady-state nature of the plasma sheet, but it also affects directly calculations of instabilities and growth rates in the plasma sheet since previous work has assumed Maxwellian distributions. ISTP will provide a measure of the steady-state distribution throughout the plasma sheet to distances of $\sim 250 R_E$.

The objective of this study will be to survey the magnetotail from Earth to $250 R_E$ during periods of geomagnetic calm. The requirements to complete this study are: Geotail observations throughout the length of the magnetotail, simultaneous Wind observations of the solar wind, Polar observations of the auroral oval, and Cluster observations of small-scale structure in the near-Earth magnetotail. A further requirement is a significant amount of magnetotail observations during geomagnetically quiet intervals. The success criterion for this study will be comprehensive description of the magnetotail structure and processes during periods of geomagnetic quiescence.

Studies of the magnetotail during calm intervals will proceed in three directions: the study of features as yet unknown and unreported, determining in greater detail the characteristics of processes known to occur during quiet periods, and determining whether processes observed during disturbed intervals cease. At this time, we cannot even guess what new phenomena will be observed with the well-equipped satellites and multipoint observations of the ISTP program. Concerning previously observed phenomena, we may take as an example the ISEE observations of possible filamentary structures that protrude from the plasma sheet into the magnetotail lobes and the DE observations of sun-aligned arcs during quiet intervals. What we do not know is if or how these features are related and how they might map to one another. ISTP observations will be essential in answering such questions. In addition, the multipoint Cluster observations will help determine the occurrence, extent, and structure of the filamentary features within the lobe, their growth, and motion.

There is an enormous array of questions to be answered concerning how processes known to occur during disturbed intervals might vary during quiet periods. One would expect magnetospheric convection to become more sluggish during periods of geomagnetic calm. Dayside magnetopause merging may cease, the polar cap may shrink, the mantle may

thin or disappear, the tail lobes may diminish in size. Magnetic flux may not cross the magnetopause, which would then become a tangential rather than a rotational discontinuity. Magnetotail twisting may cease or become less apparent. The plasma sheet may thicken and cool, while the cross-tail merging line may move to great distances. As a result, more magnetotail flux may close within the near-Earth plasma sheet, and the magnetotail may not extend to the Geotail apogee. The bursts of energetic particles and high-speed flows so often seen in and at the boundaries of the plasma sheet may disappear altogether during quiet intervals.

Magnetotail Current Systems

The Earth's magnetotail contains a vast network of electrical currents. Direct observations of these currents are fundamental to understanding the topological features of the magnetotail, its violent behavior during substorms, and the strong coupling of the magnetotail with our planet's ionosphere and upper atmosphere. A cross-tail current sheet embedded in the plasma sheet and straddling the neutral sheet provides the primary principal magnetic fields that extend the geomagnetic field into a downstream magnetotail. Plasma flows along the magnetotail interface with the magnetosheath at high and low latitudes drive currents into and out of the ionosphere and provide corpuscular and Joule heating of the upper atmosphere. Similarly, ions and electrons are forced into, and down out of, the ionosphere on magnetic field lines that are believed pass along the boundary of the plasma sheet. At these locations in the ionosphere bright auroral arcs can often be seen.

The convergence of magnetic field lines into the auroral zones from the magnetosphere increases the current density over the auroral and polar ionospheres and allows relatively easy detection of these currents with low-altitude spacecraft. However, the corresponding current densities within the magnetotail are sufficiently small that their direct detection has been difficult, and very sparse, with previous spacecraft. We have learned with this instrumentation designed and launched over a decade or more ago that the currents are of at least four types: (1) currents that balance pressure gradients in the plasmas, (2) currents due to pressure anisotropies along magnetic field lines, (3) direct bulk flows of ion and electron plasmas along magnetic field lines, and (4) nonadiabatic motions of ions and electrons in crossed electric and weak magnetic fields such as at the neutral sheet.

Limited sensitivity, angular coverage, and ion-composition measurements have reduced the number of direct-current measurements to a relative handful. Currents have been mostly inferred from spatial variations in the magnetic field, rather than directly measured. This kind of inference has been extremely productive and is largely responsible for our present understanding of the various current systems in the Earth's magnetosphere. However, there are several problems with this method of determining currents. First, since the current density is proportional to the curl of the magnetic field, it is impossible to obtain the full vector character of the current density from a single spacecraft. Second, the variation of the magnetic field along the spacecraft path may involve temporal change as well as a spatial gradient. Inference of the magnetic field requires assumptions about the configuration of the current distribution, e.g., a sheet or line current that is time stationary. A third problem is that the charge carriers cannot be determined from this kind of measurement.

In recent missions, notably on the ISEE spacecraft, it has proved possible in some circumstances to obtain currents by direct integration of the measured charged particle velocity distributions. This has the advantage of both identifying the charge carriers and also of providing information on the energy range of the particles carrying the current, as well as giving the full three-dimensional vector character of the current density. This technique for obtaining the current requires that the spacecraft electric potential be small so that all charged particles can reach the spacecraft with minimum distortion in their trajectories, and it also requires excellent angular and energy resolution for the particle instruments.

ISTP will provide greatly improved capabilities for measuring magnetospheric currents. First, new and improved particle detectors will have much greater energy and angular resolution together with composition determination which is required in order to obtain accurate ion currents. Second, the electrostatic cleanliness requirement and spacecraft potential control capability will greatly extend the periods of time for which accurate current measurements can be obtained. Finally, the Cluster mission of four closely spaced spacecraft will enable the full vector determination of the curl of the magnetic field at a given time, thus doing away with the previous need for assumptions about the configuration of the current system and its behavior with time.

Advances in plasma instrumentation, increases in telemetry rates, and the trajectories selected for the Polar and Geotail spacecraft provide an unprecedented opportunity to survey the currents in the magnetotail. Instead of a few hard-won determinations of the current densities, a continuous series of such measurements will be possible. This will make it possible to assess quantitatively the relationship of these vast current systems with the plasmas and magnetic fields of the solar wind and their coupling to the ionosphere and to search for the spectacular collapse of or diversion of neutral-sheet currents during substorms. Direct detection of the magnetotail currents that close in the ionosphere, along with simultaneous auroral imaging from the Polar spacecraft, will allow us to extend the *in situ* point current determinations into an instantaneous global picture of the current distributions. Although not all of these currents will leave a luminous footprint in the ionosphere, it is expected that certain ones will provide important insight into the global configuration. For example, auroral images from Dynamics Explorer 1 and plasma measurements with ISEE spacecraft indicate that the currents flowing along the boundary of the plasma sheet leave their signature as the poleward bright arcs in the auroral oval. If so, these bright arcs will give us a view of the instantaneous distortion of this current sheet and its violent motions during a substorm. Direct observations of the plasmas provide in turn both a determination of the source of the current and its ponderomotive force. Thus the capabilities for determining the current densities throughout a major portion of the magnetotail with the ISTP spacecraft will provide a fundamental advance in our studies of geospace plasmas.

Ring Current

One of the principal tasks of the original OPEN program was to understand the source and loss mechanisms of the dynamic ring current. The multi-ion nature of the storm-time ring current raises new questions about source and loss mechanisms, which remain

unanswered, even after the significant contributions of AMPTE CCE to charge and mass composition and radial profile measurements of the ring current. In the absence of the type of electric and magnetic field and wave measurements on AMPTE that were planned for Equator, our understanding of the relative importance of charge exchange and wave interaction processes remains limited. Moreover, the relative importance of the ionospheric and the solar-wind sources is species-dependent and will not be resolved until we have simultaneous measurements of the solar-wind and ionospheric inputs.

The input function is complicated to determine because there is evidence both for direct acceleration of ionospheric ions into the ring current in the low-energy O^+ pitch angle distributions and for impulsive injection from the plasma sheet, where the solar wind and ionospheric plasmas are already mixed. An equilibrium model of the ring current based on steady-state convection in from the geomagnetic tail, incorporating the quiet-time ionospheric contribution, is required as a first step. Then one could examine the dynamic perturbations which produce order of magnitude increases in ring current flux and predominance of O^+ at lower energies during geomagnetic storms.

Loss mechanisms become a more complex issue in a multi-ion plasma. Charge-exchange rates are species-dependent, as are the wave processes. Electromagnetic ion cyclotron waves have been shown to be important for H^+ loss by pitch-angle diffusion, but are not effective for ring-current O^+ loss in a plasma where O^+ is a minor cold-ion component, since O^+ ion-cyclotron waves are not excited to a large enough level to cause pitch-angle diffusion via cyclotron resonance. In a different wave frequency range, also associated with geomagnetic activity, Pc 5 micropulsations interact with low energy O^+ via a drift-bounce resonance, which can cause loss from drift shells as well as particle energization and inward diffusion. A quantitative application of these models to the recovery of the storm-time ring current to its equilibrium state requires more information on the wave polarizations than was available from AMPTE, specifically the low-frequency electric-field component of the Pc 5s, which has not been measured in the equatorial plane in concert with magnetometer and particle measurements; and there is a need for more information on the low-energy plasma component, which affects the ion cyclotron wave studies.

How then can ISTP address the objective of understanding ring-current dynamics, which is a truly global process and is central to the question of magnetospheric source plasmas? The CRRES satellite provides good coverage of ring-current ion composition, and the greatest sensitivity and highest time-resolution field and wave measurements to date in the ring-current region. Its shortcoming is the $6.3 R_E$ apogee, which limits radial coverage. The lifetime of the spacecraft and experiments relative to the launch date of the other ISTP satellites is also problematic, given CRRES' intense radiation-belt exposure. Nonetheless, CRRES represents a valuable data base for addressing the problems described above. It is critical that CRRES be integrated into the ISTP data base in a format that is network-accessible and compatible with data from the other ISTP spacecraft if comparisons between ionospheric (Polar, FAST) and solar-wind (Geotail, Wind, Cluster) sources of ring-current plasma are to be made. In terms of loss mechanisms, CRRES may be the only satellite instrumented for the appropriate wave measurements in the equatorial

region during ISTP, unless Regatta-E or Equator-S materializes and is appropriately instrumented. The Los Alamos geosynchronous satellites will provide information on the ring current and total low-energy plasma density during ISTP, but will not furnish magnetometer or other wave data.

What will be the success criteria of ISTP for the above equatorial science? A definitive answer to the relative importance of the solar-wind and ionospheric source plasmas at solar minimum is one. The relative importance of charge exchange and wave loss processes is another. The availability of mass-composition measurements at ring-current and plasmaspheric energies will affect the ability to close loopholes and be definitive about the above source and loss candidates. Additional information on plasmaspheric densities and location of the plasmopause lacking in the present spacecraft configuration may be obtainable from ground-based measurements if these are supported and incorporated into the ISTP data base on the same footing as satellite experiments.

Auroral Oval

The magnetic field lines in the auroral and polar ionosphere extend into the plasma domains of the distant magnetosphere. The auroral and polar emissions are the only visible manifestations of the presence of these magnetospheric plasmas. An accurate mapping of these magnetic field lines into the magnetosphere can provide a global reference for the general position, sizes, and motions of regions and boundaries such as the polar cusp, magnetopause, plasma sheet and its boundary layer, and the magnetotail lobes. In an ideal map, unique types of luminosities could be used to identify each of the magnetospheric plasma features. In fact, global auroral images from Dynamics Explorer 1 have successfully provided several of the primary features of this map, e.g., polar arcs associate with the plasma-sheet boundary, diffuse electrons from the inner plasma sheet, and a measure of the total magnetic energy in the magnetotail as gauged with the magnetic flux through the area within the poleward boundary of the auroral oval.

The ISTP spacecraft will substantially fill in the details of the mapping from the auroral ionosphere into the magnetosphere. The verification of these mappings requires that a spacecraft detect a region in the magnetosphere, e.g., the polar cusp, simultaneously with imaging of the ionospheric luminosities. Then a magnetic field model is used to follow the *in situ* measurement to the corresponding luminosity feature. The Polar spacecraft is equipped with advanced cameras for ultraviolet and visible emissions with capabilities far beyond those of previously flown imagers in the areas of spatial resolution, frame rate, and spectral resolution. X-ray imaging will also be performed, complementing the imaging performed at UV and visible wavelengths. Emissions from proton precipitation into the ionosphere will be imaged globally for the first time and allow simultaneous mappings of the footprints of ions and electrons from the various magnetospheric plasma regions.

Images of the auroral-oval and polar-cap emissions provide the unifying reference frame for global magnetospheric studies with the host of spacecraft providing *in situ* measurements. This reference frame is dynamic and continually fluctuating, and the images provide not only a spatial reference frame but a very effective time-line for the phases of magnetospheric substorms.

The region where particle acceleration is best understood is the auroral oval. The high-time-resolution three-dimensional electric field measurements made there by S3-3 and Viking have been able to identify the structures (double layers and electrostatic shocks) where electron and ions are energized by the parallel electric field, and particle simulations and analytic theories have provided a qualitative understanding of the formation and evolution of the structures. Heating of plasma by waves and the excitation of waves such as auroral kilometric radiation by the accelerated electrons has also received intense theoretical and experimental attention. The closure of theory and experiment in this area provides a model for ISTP.

Many important questions, however, remain unanswered because the required high-time-resolution electric and magnetic field, plasma and composition data were not available. In order to understand the inherently nonlinear structures such as double layers, high-time-resolution electric-field data must be examined in the time domain, and simultaneous particle data including composition must be obtained for certain ranges of pitch angles and energies that vary depending on which particular phenomenon is being studied. The flexible instruments and burst memories on Polar, FAST, and Cluster will do this. Examples of the questions that will be addressed by ISTP are the following: 1) What is the distribution of the parallel electric field in electrostatic shocks and double layers? What is the altitude range of parallel-field acceleration? What are the effects of variable ion composition on these structures? 2) Are ion conics accelerated in electrostatic shocks, which results in phase bunching, or in waves such as lower hybrid or electrostatic ion cyclotron waves? If the latter, which waves are the most important? What are their wavelengths? Are the heating processes linear or nonlinear? How far up the field lines does heating occur? 3) What are the important wave modes in the auroral zone at different altitudes including wavelengths, sources of free energy, and effects on particles? What wave/wave processes occur? 4) What are the detailed distributions unstable to auroral kilometric radiation? What produces the time-variable fine structure that has been observed in the spectra (double layers, maser cavities etc.)? 5) What are the sources of the diffuse aurora? 6) What causes flickering aurora?

Magnetosphere/Ionosphere/Thermosphere Interactions

The new instrument capability that ISTP auroral imaging presents, allows us to make a fundamental step forward in our ability to transform the images into images of primary parameters that describe the precipitating particles (e.g., flux and characteristic energy). These images can be used to identify periods of interest for overall study by ISTP, can be used to infer the properties and origins of processes taking place within the magnetosphere, and allow us to improve greatly our ability to model the global ionosphere and thermosphere. For example: The solar-wind/magnetosphere dynamo produces large-scale currents in the magnetosphere that ultimately close by flowing through the ionosphere. The high-latitude potentials that result cause the ionosphere to be convected in response to the magnetospheric processes. The precipitation of corpuscular energy and the convective electric fields force both the ionosphere and neutral atmosphere (thermosphere and mesosphere), resulting in winds, strong heating and composition changes. To date the corpuscular and convective fields have represented major missing elements of our modeling

ability and have, by necessity, been assumed or checked in spot locations. With the ISTP database, we will have the ability to generate the corpuscular and Joule heating and the high-latitude convection patterns of the ionosphere on a global scale for the first time.

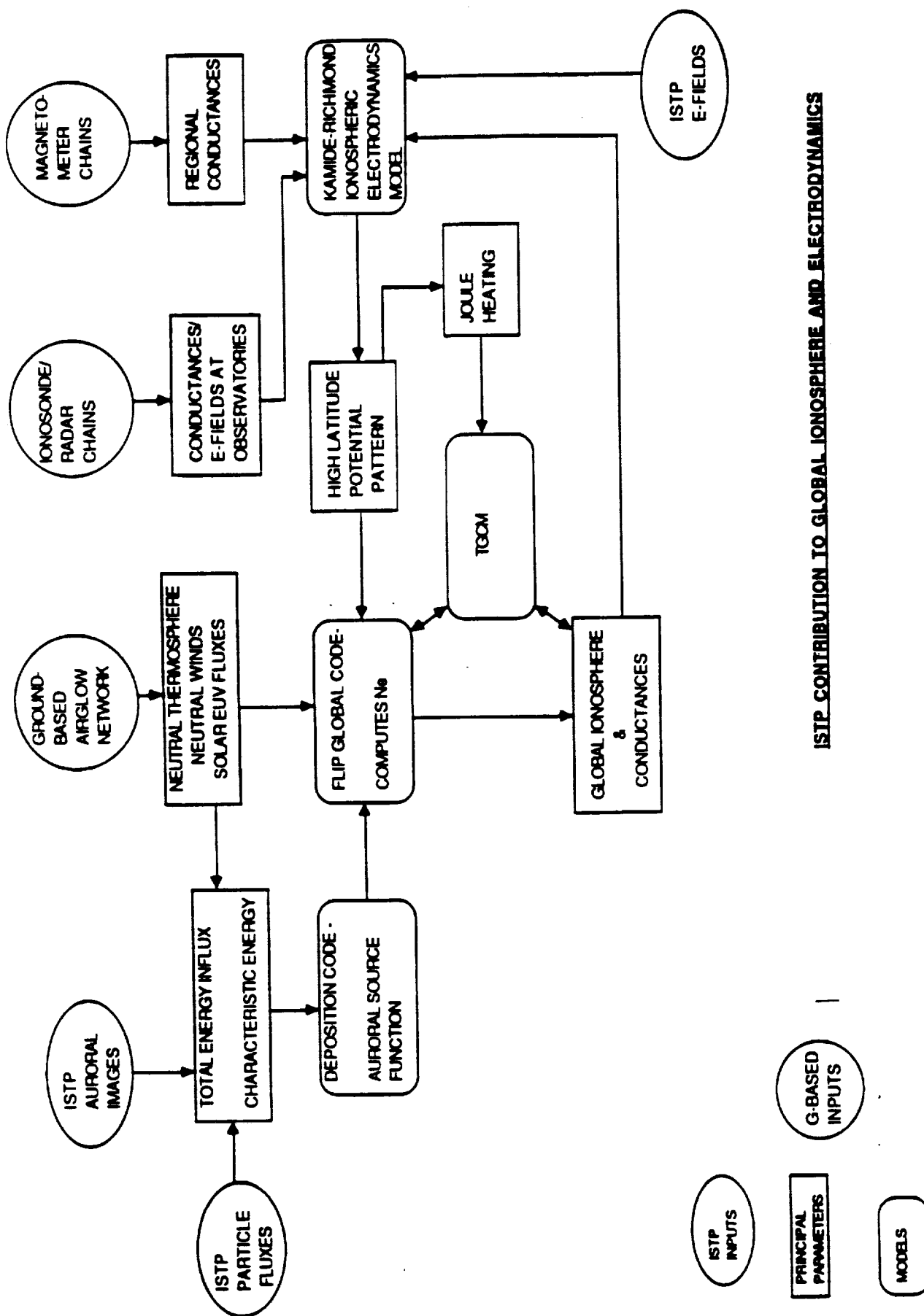
How this might be done is illustrated in Figure 7. Starting at the top left, ISTP will provide global (simultaneously acquired) images of the sunlit and dark auroras. With the appropriate knowledge of the thermosphere, these can be transformed into images of energy influx and characteristic energy of the precipitating particles. At the lower altitudes of the Polar spacecraft (i.e. below the acceleration regions), it will be possible to verify these parameter images against the direct particle measurements made at the spacecraft. With this information and an auroral energy deposition code, the ionospheric source function (ionization rate) can be computed. This information can then be used by a global ionospheric/thermospheric code to compute the global electron concentrations. Having the electron concentrations, we can compute the conductance—a fundamentally important parameter, because this tells us how the magnetospheric currents close through the ionosphere.

However, the modeling necessary to reach this point is dependent on models of the neutral atmosphere, the neutral winds, and the solar extreme ultraviolet flux; all of which are parameters that will not be measured by ISTP or not measured at the same time as the Polar measurements are made. We can obtain confirmation on the first of these, the concentrations of the major neutral species, at single point locations by making coordinated airglow measurements from the ground. Similarly, from ground-based ionosonde stations we can extract the meridional component of the neutral winds. As has been mentioned above, actual measurements of the solar EUV flux are most important. At the present, there is no plan to provide these during the Polar operating period, and models will have to be used.

Once we have the ionospheric conductances, these conductance images together with the ISTP electric field measurements, can be used as input to an ionospheric electrodynamic model to compute the high-latitude potential pattern. This pattern is now fed back into the ionospheric code as an additional constraint on the conductance calculations.

Going further, once we have the high-latitude potential pattern, we are able to compute the Joule heating of the ionosphere, which is comparable in magnitude to the heating caused directly by the precipitating energetic particles. The Joule heating together with the high-latitude potential pattern, when fed into a thermospheric global climate model, allows us to model the winds and composition changes in the neutral atmosphere that result from the magnetospheric and solar-wind processes.

The auroral phenomena that we are attempting to interpret are superimposed on an airglow and neutral atmosphere background that are dependent on the solar EUV flux. In the end, our knowledge of this principal thermospheric source function will limit the accuracy with which we can achieve our objective of modeling the time evolution of the ionosphere/thermosphere response to the magnetospheric events. Measurements of the solar EUV flux are planned only for the SOHO spacecraft. Carefully planned acquisition of



ISTP CONTRIBUTION TO GLOBAL IONOSPHERE AND ELECTRODYNAMICS

Fig. 7. Schematic showing how ISTP data will be used, together with data from ground-based facilities and with global circulation models, to produce a quantified understanding of the propagation and deposition of energy and momentum in the Earth's ionosphere and upper atmosphere.

SOHO EUV data during the period of overlap between SOHO and Polar will therefore be crucial to the accomplishment of the auroral energy deposition objectives of ISTP.

In summary, for the first time, we will be able to model the moment to moment evolution in time of the global ionosphere/thermosphere in response to magnetospheric forcing.

V. APPROACH

Organizing the ISTP Research Program

As noted above (Section II, B), a comprehensive research program for solar-terrestrial physics must progress through the following sequence of levels: 1) learn the parts, 2) determine how they work, 3) see how they are connected, 4) assemble them into a working model, and 5) run the model and check its predictions. For the purpose of organizing scientific planning, the ISTP program can be divided into four parts—a prelaunch part and parts for three groups of research levels: levels 1 and 2 together, level 3, and levels 4 and 5 together. This division is based on a difference in purpose between the prelaunch and later parts and on differences in research modes among the three groupings of research levels.

Prelaunch research activity has two facets: (1) soliciting model development and (2) implementing a trial shake-down of the ISTP data analysis system. Regarding the first, the project will solicit models identified as *project needs* and *models submitted for project testing*. Of the former, and foremost among these, the project will need magnetic- and electric-field models, like the Tsyganenko and Voigt models, with an array of input parameters, such as boundary positions and substorm phase. Responsibility should be assigned to a project scientist to identify model needs and to authorize advancing, modifying, or, if necessary, developing models to meet these needs. The project will also solicit scientists to submit models whose predictions or simulations can be tested with project data. Such tests represent one means for the project to carry out the business of data-theory closure.

A prelaunch trial shake-down of the ISTP data analysis system should be conducted with the PROMIS data base, which closely approximates the planned ISTP data base. Running the PROMIS data set through the ISTP data analysis system not only simulates handling ISTP data types, it represents addressing ISTP types of science. Thus, in advance of the ISTP mission, the ISTP project can produce important science.

The prime responsibility for organizing ISTP science objectives pertaining to research levels 1 and 2 should devolve onto individual PI teams and groups of PI teams from individual spacecraft. Yet theorists and modelers of space plasma physical processes also need to be integrated into the research plan. Except for that relating to the participation of theorists and modelers, the space physics community has traditionally assumed the stated responsibilities. Thus, except for assuring greater involvement of theorists and modelers, the project need be involved only minimally in organizing research efforts at these levels.

At research level 3, the project needs to organize coordinated data analysis programs that integrate PI teams from more than one spacecraft and an associated contingent of theorists and modelers in a preplanned series of full-up data reduction and analysis intervals (with likely associated ground-based campaigns) and subsequent workshops. Each major scientific objective at research level 3 will receive such a project science program. The project will be able to enumerate a named set of such projects and state each program's agenda for implementation. The project will be able to announce when phases 1, 2, etc., of

a program have been executed, and relate the extent to which program objectives have been achieved.

Research levels 4 and 5 mainly entail organizing a series of theory and modeling workshops with participation from observers to develop the most physically explicit models of interactive magnetospheric dynamics, leading to a comprehensive model for the entire system which has been extensively tested using data and which has a predictive capability. A second, but very important objective of research at these levels in the ISTP program is to determine with greater precision what the post-ISTP requirements are for geospace missions intended to operate mainly on research levels 4 and 5.

Facilities and Operations

The coordinated operation of the complex suite of ISTP spacecraft and the acquisition of the appropriate science data will require the implementation of the majority of the basic "tools" already identified and recommended by the IACG for this purpose. These include the Science Planning and Operation Facilities associated with each project, Satellite Situation Centers, Mission Operation Facilities, data networks, data exchange, visualization and analysis tools currently under development and test, central data handling facilities, geophysical data bases, etc.

The concepts behind these tools are illustrated in Figure 8. The basic tools associated with the flight projects are the respective spacecraft and selected investigations and investigator teams. The operations of the spacecraft are generally the responsibility of a Mission Operations Facility (MOF) which manages the appropriate resources to ensure that the spacecraft are tracked and the necessary data acquired and delivered to the investigators. In parallel with the MOF, a Science Planning and Operations Facility (SPOF) is responsible for all aspects associated with the commanding, configuration and operation of the flight instruments or ground-based investigations. The primary objectives of the MOF are the correct operation of the spacecraft and tracking facilities as engineering systems, while the SPOF is responsible for assuring that the scientific instruments are operated in a manner consistent with the project's science objectives, both specific and/or coordinated by the IACG.

The formal categorization for compatibility of SPOFs across IACG missions has not been finalized yet and is currently under definition by WG2. In general these are modest, interactive computing facilities based on scientific workstations. The Principal Investigators of each mission communicate to the respective SPOF the required instrument configuration and operational commands necessary to assure that the appropriate science data are generated onboard the spacecraft (Science Operations Plans). After processing, data files recording the configurations and operating modes of the instruments are generated for later access by the investigators. Coordinated operations among the multiple IACG missions are carried out by project-to-project (SPOF-to-SPOF) communications under the general oversight of the respective Science Working Groups (SWG's) and Project Scientists, who provide the necessary evaluation of tradeoffs between conflicting science requirements, optimal use of project resources and overall science goals.

IACG "TOOLS"

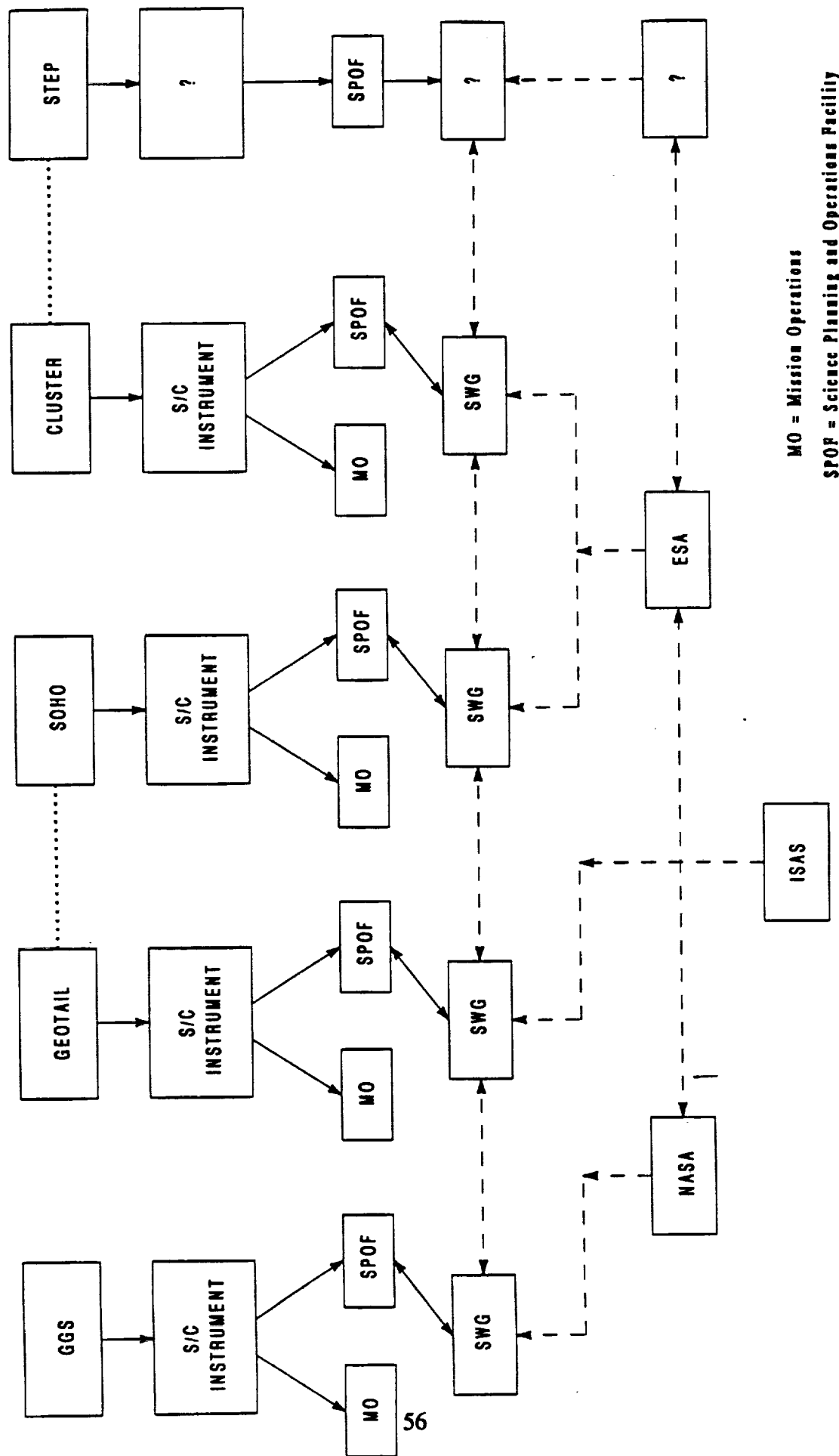


Fig. 8. Schematic illustrating the infrastructure being developed under IACG guidance for the coordination of ISTP mission operations and data exchange.

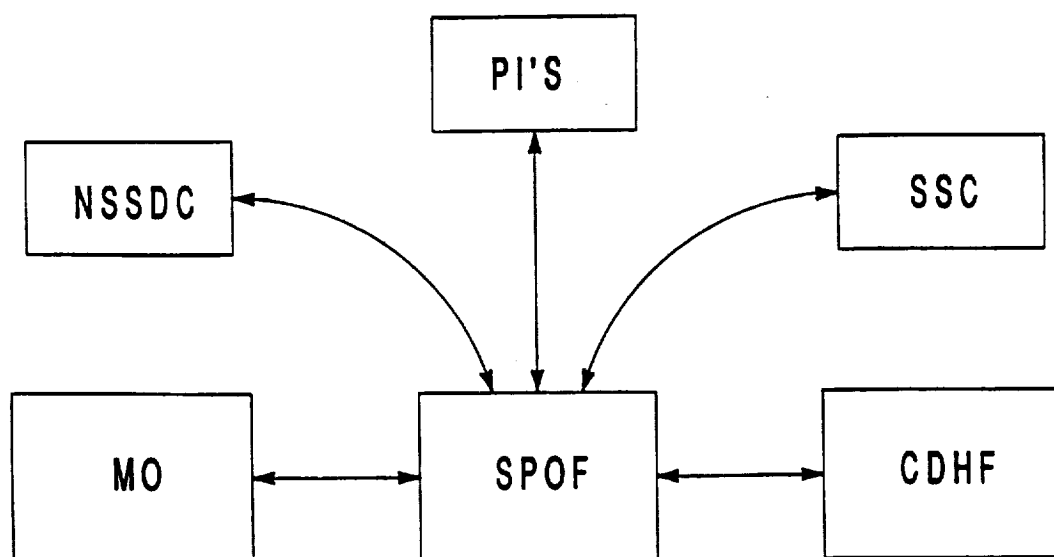


Fig. 9. Schematic summarizing some of the functions of the Science Planning and Operation Facility (SPOF) that will be associated with each ISTP project.

Although the capabilities of each SPOF need not be identical, a desired configuration for flight missions coordinated by the IACG is the capability to produce “key” or “summary” parameters from the science data. These are low-time-resolution data sets, extracted from the science data stream, which provide a broad overview of the geophysical quantities being measured and which are available on a reasonably short time scale. It is proposed that access to these summary or key parameter files be carried out with a set of (eventually “IACG” recommended) software tools currently under study by the GGS, Geotail and Cluster projects, among others. This approach will facilitate the exchange of summary data sets among the different core mission scientists and will allow easier access to high-time-resolution, highly processed data sets required for detailed study of solar-terrestrial phenomena.

In Figure 9 we have summarized some of the functions anticipated to be implemented in the ISTP, Geotail and STSP SPOF’s. Central to them are the short- and long-term Science Operations Plans reflecting immediate and long-term instrument requirements and overall objectives, the access to orbit computations, geophysical models, ancillary data bases, and other data required for science planning and coordination. It is anticipated that the GGS SPOF will play an essential role in the monitoring of the scientific accuracy of the key parameter files as well as provide essential guidance for conflict and tradeoff resolution.

It is important to note that scientific direction and prioritization for the SPOF activities will be provided by the respective Project Scientists of the core missions, following recommendations from the Science Working Teams and overall guidelines provided by the respective space agencies.

The accomplishment of the overall coordinated science objectives also requires the utilization of existing electronic data networks for the exchange of science operations information among the core missions as well as limited summary data necessary for science planning and evaluation. Although the present ISTP data transport, display and analysis standardization effort follows IACG preliminary recommendations, it is limited primarily to key parameter data produced under configuration control in a Central Data Handling Facility and not to data produced by investigators at their home institutions. It is clear to the scientific community that this effort is just a beginning and to realize fully the potential of the coordinated observations and data analysis, additional data transport, visualization and analysis tools must be studied and recommended by the IACG for implementation across its wide range of data products and missions. This task falls under the general activities assigned to WG2.

In addition to the above, the importance of incorporating ground-based observations within the scope of IACG-coordinated activities, has been emphasized by the US solar-terrestrial physics community. The Solar Terrestrial Energy Program (STEP) is a particular example that will be capable of providing essential data to complement the IACG spacecraft observations. However, in order to make full utilization of the acquired data, it is recommended that these ground-based investigations adopt to the largest extent possible the concepts of key parameter data set generation, identify associated SPOFs for operations coordination, and participate in the study of data visualization and analysis tools as adopted by the IACG.

The role that the IACG will play in the area of data transmission, processing, analysis and archiving is fundamental. Just identifying constellations of spacecraft, orbits, and operating modes is not sufficient to accomplish the desired goals. The IACG must actively promote the development and test of information processing "tools," which provide synergistic, efficient and cost-effective access to data sets, their visualization and eventual analysis, leading to a significant understanding of the solar-terrestrial system. This is a minimum criterion of success. Just having the spacecraft in place and the instruments operating in the right modes will not accomplish the scientific goals of the "core" missions. These requirements are complemented by the contemporary availability of numerical simulation and modeling tools which will play essential roles in the interpretation and understanding of the acquired data and in a theoretical extension to regions not accessible to the spacecraft complement. The IACG has already recognized their importance and must continue to endorse their application to the core mission environment.

Mission-Oriented Theory

From the start, theory and modeling have been fully integrated into ISTP planning, and it was realized that *mission-oriented theory* had to be different from the type of theory supported under the Space Physics Theory Program or the Research and Analysis Program.

The goal of *conventional theory* is to understand basic physical mechanisms; here the theorist conceptually integrates or generalizes from many observations to formulate relatively general models which capture the essential elements of some physical process.

The goal of *mission-oriented theory* is to develop techniques and models that can be used by experimentalists and theorists to interpret specific spacecraft measurements, deducing from them information about both local and large-scale dynamics.

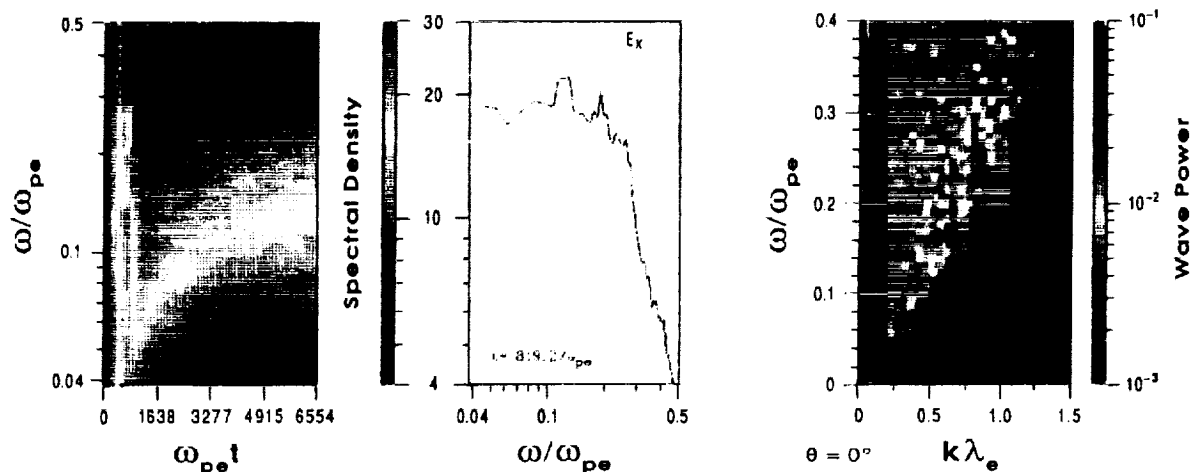
Theorists recognize that to be effective they have to communicate with experimentalists in their language, and not in the language of pure theory. Clearly, the first objective for mission-oriented theory is to develop new simulation diagnostics which, to the extent possible, parallel the data-display formats used for spacecraft measurements. As an example we show results of an ion beam-driven system, which is intended to model the generation of broadband electrostatic noise (BEN) in the plasma sheet boundary layer. Both wave and particle diagnostics are presented (Figure 10) and the display format consists of a frequency-time or swept frequency receiver (SFR) diagram over the duration of the simulation, color coded in wave intensity on the top, and in energy-time spectrogram format on the bottom.

Satellite wave instruments may not obtain a direct measurement of the wave number (k), whereas in simulations the spatial modes are the fundamental quantities. To exploit the information available from simulations, we calculate the wave dispersion relation (ω versus k), and by comparing the simulation output with linear wave theory we can clearly identify which modes are excited by the instability and understand coupling interactions between different wave modes. Moreover, knowledge of the frequency and wave number of the fastest growing mode allows us to determine the particle resonant velocities. Having deduced the resonant particle velocities, the plasma experimentalist can isolate the resonant regions of the measured particle distributions and carefully analyze them for evidence of the expected wave-particle modification of the shape of the distribution function.

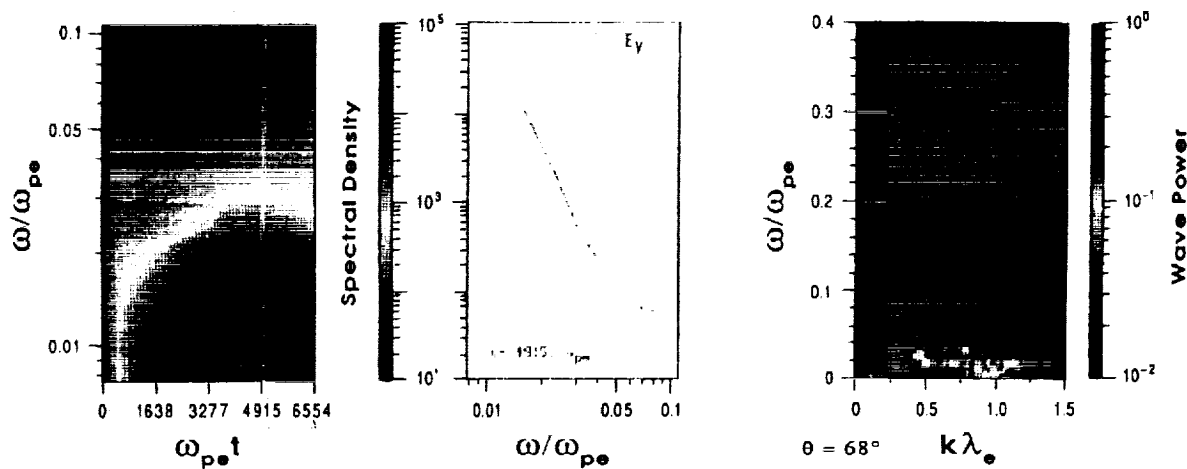
One thing that was clear from the very beginning of the program was that MHD models would be an essential component of the ISTP mission, since they provide information about global transport. They are a means of linking measurements made in very different regions of the magnetosphere because they contain large-scale cause-and-effect behaviors, and one can relate measurements taken at one time with events that happened before and those that will occur after. In order to facilitate the initial comparison with the ISTP satellites, time histories of simulated "generic" states of the magnetosphere will be stored on optical disk, which can be used to create dynamical displays of both local parameters and the global configuration.

Although the goal of the MHD modeling program is to assist in the global interpretation of the spatially-distributed ISTP spacecraft measurements, we should anticipate that in many instances these measurements will not be adequately described by any of the stored generic MHD simulations. The variability of the solar wind and the hysteresis of the magnetosphere combine to prevent the system from ever achieving an idealized state. The output of the stored generic models, therefore, will more nearly resemble "quick-look"

Electron Acoustic



Ion-Ion Acoustic



Electron Cyclotron Harmonics

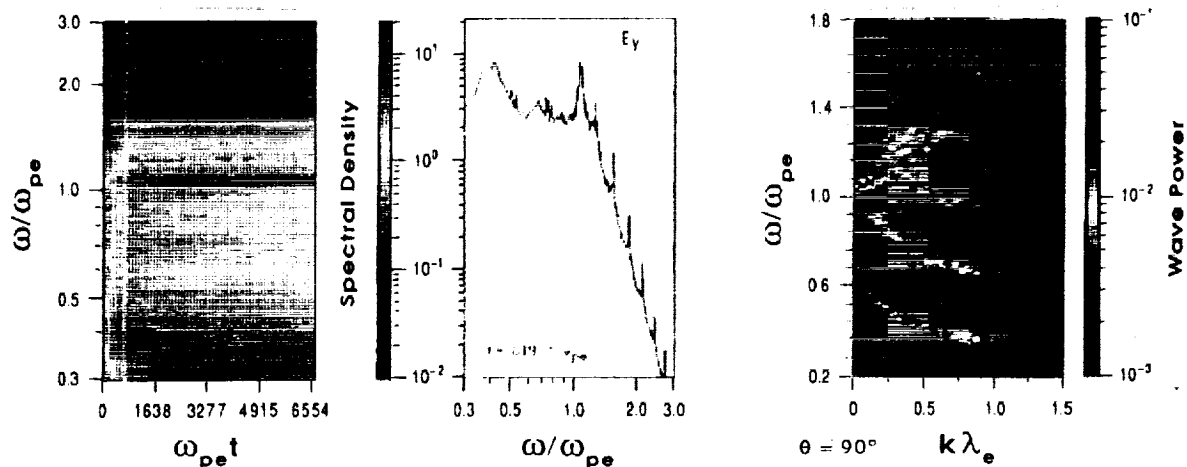


Fig. 10. Results of a wave analysis from a self-consistent numerical simulation of the plasma sheet boundary layer. The simulation diagnostics attempt to parallel the data-display formats used for spacecraft measurements.

data, which can help to locate the spacecraft relative to the large-scale boundaries and structures and to select interesting events by allowing the experimenter to make an early identification of the relevant signature in the measurements. They can provide an initial determination of cause and effect, and thus establish a framework around which to construct a detailed research effort.

By storing the kinetic and MHD simulation data on optical disks, these theoretical tools become readily available to all ISTP investigators to assist in the interpretation of measurements. Although theorists and experimentalists can continue to operate independently (as in the past), we suspect that this new theoretical technology will foster much closer collaborative efforts. For example, in selecting specific events for intensive study, an immediate issue will be to determine whether the measurements are readily interpretable in terms of the existing models. They probably will not be. The question will then be whether small changes in the model yield the desired agreement or whether a fundamental disagreement between model and measurement exists. In either case the event would be deemed worthy of further study, and progress will require close interaction between experimentalists and theorists.

As part of the ISTP theory effort, new simulation techniques will be developed that directly incorporate kinetic effects of particle distribution functions into global MHD modes such as micropulsations. In particular, hybrid codes are being developed wherein one particle population such as the energetic ion ring current is treated with particle simulation techniques, from which a pressure is calculated and fed into a three-dimensional dipole MHD code in order to understand how resonant particle populations can be generated and be affected by large-scale MHD modes of the magnetosphere. Local measurements of the ion composition and distribution functions will be required along with low-frequency electric and magnetic field measurements to test such models. However, an opportunity exists with the multispacecraft ISTP configuration to distinguish between micropulsations generated within the magnetosphere by resonant particle effects and those which propagate in from pressure disturbances in the solar wind impinging on the magnetopause. This could be accomplished with a combination of data from Wind/Polar/Cluster and data from either CRRES or Regatta-A, where there is a temporal overlap. Such studies can be planned for the ISTP mission, in contrast to past studies which relied on the fortuitous conjunction of spacecraft which lacked the more complete set of instrumentation which will be available to ISTP. Such a study will be feasible with the coordination of key parameter data from the various ISTP spacecraft into a Central Data Handling Facility, as is planned. This data set will pinpoint periods of interest, and provide enough information about global MHD wave modes to distinguish between internally and externally generated oscillations. Further examination of higher-time-resolution particle distributions can then be sought for the periods of interest in order to test the models.

Coordination with Ground-Based Facilities

Of key importance to achieving the objectives of ISTP in the area of the magnetosphere/ionosphere/atmosphere coupling will be the participation and coordination of ground-based facilities and the tying together of existing major ionospheric/thermospheric models. This will require the formation of an appropriate study

team for the purpose of defining and implementing carefully selected campaigns of observations. During these coordinated observing periods, the ground-based facilities and space instruments will be appropriately scheduled and optimized. A processed data set will be produced and iterated through the various models.

PROMIS as Prelude to ISTP Data Analysis

The ISTP will provide a large set of data from multiple satellites, including images of the auroral oval, and from many ground facilities. A major objective of the mission is to improve understanding of the mass, energy, and momentum flow through geospace by correlating data from these various sources, often using the auroral images as foci of the combined data. Such multipoint data correlations, together with appropriate models of the magnetic field, ideally allow cause-and-effect coupling to be inferred among satellites in the magnetosphere or solar wind and points on the Earth. Successful handling of this large multiple-source data system represents a formidable task of computer organization.

A data set quite analogous to that expected from ISTP was gathered during the PROMIS campaign in March-June 1986, which utilized an opportune array of 15 satellites and multiple ground facilities. Two of the satellites, Viking and DE-1, provided images (sometimes simultaneously) of the northern and southern auroras. The objective of PROMIS, like that of ISTP, was to acquire a body of data suitable for use in global-scale studies of the solar wind-magnetosphere interaction. Initial studies of the PROMIS data set done in the CDAW-9 series of workshops, have provided important new insight to magnetospheric substorm processes, while utilizing less than 5 percent of the interval of acquired PROMIS data.

With the launch of the first ISTP satellite (Geotail) still 1 1/2 years away and the completion of the total ISTP array still 5 or 6 years away it seems that much important scientific research, highly relevant to the problems ISTP is to address, could be accomplished in a "pre-ISTP" program of fuller analysis of the PROMIS data set. For example, time-dependent magnetic field models will be a necessary tool for relating observations in the outer magnetosphere to concurrent auroral images. While such models do not presently exist, initial progress toward developing them has been made in CDAW-9 analyses of PROMIS data. In addition to providing important new scientific information on which to base ISTP research, such a "pre-ISTP" program would provide ISTP team members and students with valuable experience in scientific interaction and data correlation that would pave the way for a smoother transition into the ISTP activities.

Finally, the PROMIS data set should be treated as a permanent supplement to the eventual ISTP data set and be retained in the NSSDC for use in support of studies which may be suggested by the ISTP observations.

VI. FOUNDATIONS FOR THE FUTURE

By the late 1990s, the full potential of the ISTP program will have been realized. The average internal structure of the Sun will have been determined and the interior convective motions characterized by the full implementation of the helioseismology technique. Through measurements of coronal magnetic fields, temperatures, and densities, the first global model of solar-wind generation will have been developed. Multipoint measurements in the bow shock and foreshock regions will have characterized the turbulent plasma phenomena that control the flow of energy through these first outposts of geospace. The composition, and hence the sources, of the counterstreaming ion beams in the foreshock will have been determined. The mechanisms for transferring plasma, momentum, and energy through the magnetosheath and into the magnetosphere will have been characterized and the importance of the various sources and transport channels of magnetospheric plasma will have been determined quantitatively. A first-order quantitative model of solar-wind/magnetosphere coupling, including the magnetospheric substorm, will have been formulated using a large multispacecraft data base and global simulation models. The global response of the ionosphere and upper atmosphere to the deposition of energy by magnetospheric phenomena and especially auroral particles and currents will have been modeled quantitatively.

One may ask now what can and should be done after ISTP and wonder whether or not we should wait until after ISTP to decide. An intensive study of these questions was conducted by a large segment of the space physics community under NASA sponsorship in 1990 (cf. Space Physics Strategy Implementation Study). A significant part of that study involved looking beyond ISTP at the issues and technologies that will be crucial to obtaining an eventual total understanding of the solar-terrestrial system and an operational model of it. It was found that the future studies of the solar-terrestrial system and the technologies needed to carry them out can be defined now, and it is now that these missions should begin to be developed so that the continued rapidly advancing state of knowledge about the Earth's space environment can be assured.

By region, the goals to be addressed by the future solar-terrestrial missions are as follows:

The Sun

- Perform high-resolution visible, UV, and x-ray imaging of the solar photosphere and corona on spatial scales down to 100 km in order to trace the interaction of magnetic fields and gas motions in the photosphere and the response of the overlying atmosphere in terms of heating, motions, shock waves, flares, and the solar wind (Orbiting Solar Laboratory).
- Obtain simultaneous, three-dimensional views of the Sun from over the poles and from several locations around the 1 AU orbit in order to investigate the global solar mass ejections and their influence on the solar system (Global Solar Mission).

- Make in situ measurements within 4 solar radii of the Sun to determine the specific processes (e. g., wave-particle interactions) that heat the corona and those that accelerate it to form the solar wind (Solar Probe).

The Magnetosphere

- Apply the multipoint Cluster concept to other regions of the magnetosphere, including the low-latitude dayside magnetopause, the high-latitude magnetopause downstream of the cusps, the auroral acceleration region, and the near-Earth and distant magnetotail (Grand Tour Cluster and Auroral Cluster).
- Apply EUV and energetic neutral atom (ENA) imaging techniques to image as many magnetospheric plasma regions as possible while the in situ Cluster-type measurements are being made (Inner Magnetosphere Imager and ultimately imagers of the outer magnetosphere).
- Perform comparative magnetospheric studies (Mercury Orbiter).

The Ionosphere and Upper Atmosphere

- Use comprehensive remote-sensing techniques to characterize in detail the structure and dynamics of the ionosphere, lower thermosphere, and mesosphere (Thermosphere, Ionosphere, Mesosphere Dynamics Mission) and multi-spacecraft in situ measurements (Ionosphere, Mesosphere, Thermosphere Coupler) to obtain a quantitative global model of these regions.

APPENDIX

The Process of Doing Global Geospace Science

From its fledgling beginnings in the 1960s, global solar-terrestrial physics has grown to a relatively sophisticated state. Over the past decade we have seen the concurrent collection of data from as many as a dozen well-instrumented spacecraft, along with extensive ground-based data sets. Unfortunately, such periods of great coverage have been very limited and we have not always had the requisite comprehensive observations for the most geophysically interesting periods.

One approach that reached fruition during the 1980s was the Coordinated Data Analysis Workshop, or CDAW. There have been nine CDAW series to date, each growing in sophistication and power. Each of the workshop efforts have contributed substantially to our understanding of solar-terrestrial physics and, just as importantly, each has taught us crucial lessons in how to study results from multiple instruments from multiple spacecraft or ground-based platforms. What we have seen in the CDAW experience is that there existed extraordinarily difficult hurdles to cross before the process of basic science research could really begin.

In the recent CDAW program, the challenges to even begin the data analysis have been formidable. First, the science community has had to agree in some general sense about what classes of problems were most important to study. In most cases, the subject of global magnetospheric dynamics (i.e., substorms and geomagnetic storms) have proven most amenable to the CDAW approach. Having agreed on a science problem, it is then necessary to identify suitable events to analyze and thereby address the problem. In the past, the data necessary to even *identify* the interesting event intervals have been spread worldwide in the individual investigator institutions. It has been a long and painstaking process just to get a first cursory look at the key data necessary to arrive at a short list of possible events.

Once the likely analysis intervals have been found, there then has been the long, painful period of data assemblage and data ingestion into a central facility (for CDAWs this was the NSSDC at NASA/GSFC). Every data set has had different formats and every data submission took special effort by the investigator team. In the case of auroral imaging data—which are crucial for proper event identification—only rudimentary information was typically available at the early stage of CDAW-8 and CDAW-9. Generally, it was only late in the detailed analysis phase that full-resolution, corrected geomagnetic representations in gridded coordinates were available to the author teams of the CDAW efforts. Moreover, the full access to data—whether imaging or time series data from particles and fields sensors—was often possible only by going physically to the NSSDC at the prescribed time of a CDAW meeting (2 or 3 days every several months, at most).

The net result of all of this was a very cumbersome system in which it took months (or years) to even agree upon a problem area and to identify events to address the problem. Then, there was another period of many months when data were gradually submitted and

collected in the central data base. After many fits and starts by NSSDC personnel to successfully ingest data, the first comprehensive survey plots would emerge so that researchers would finally be able to see for sure what kind of global event they had "in captivity." With CDAW meetings only a few times per year, the final analysis also progressed slowly, implying that the ultimate scientific payoff was very delayed, indeed, for these gargantuan efforts.

In contrast, we now envision with ISTP a time when we can short-circuit much of the delay that has previously existed in carrying out global geospace science. We see the planning and rapid development of a centralized system of data collection, processing, and visualization that will allow us to identify and select events almost instantaneously. We see the continuous production of key parameters from all flight instruments and many ground-based systems which will be available to all ISTP investigators and theoretical modelers. We expect to have all available images of the aurora in a convenient, readily interpretable form so that the most interesting periods can be zeroed-in on very rapidly. We expect reasonably continuous coverage from the ISTP spacecraft so that we do not have the heartbreaking data gaps in key physical or temporal regions that have so inhibited research success in the past. We expect that the new generation of science instruments on ISTP spacecraft will give us unprecedented spatial, temporal, spectral, and compositional information about the solar-terrestrial system.

It is the exciting, emergent view of our community that a genuinely brand new era is dawning for the discipline of solar-terrestrial science. It will be as if we have suddenly come from the stone age to the information age in the space of just a few years. The primitive, time-consuming preparatory efforts of the past where it took us months or years to precondition our data bases to begin the scientific inquiry will now be done in days or weeks. We can finally bring to bear our most precious science—our intelligence and scientific curiosity—without bogging ourselves down with seemingly endless preparatory activities. When we further realize that we now have far more developed empirical and theoretical modeling tools than have ever been available in CDAWs, we can truly say that ISTP represents a new era in global space science.